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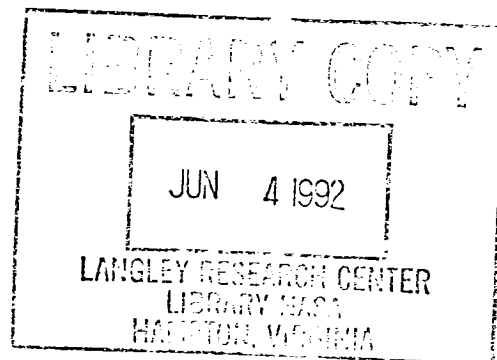
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STRUCTURAL MARGINS ASSESSMENT APPROACH

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Science and Engineering Directorate

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16. ABSTRACT This document contains a general approach for structural design and verification used for determining the structural margins of the space vehicle elements under Marshall Space Flight Center (MSFC) management. The Space Shuttle results and organization will be used as illustrations for techniques discussed. Discussed are (1) the system analyses performed or to be performed by and (2) element analyses performed by MSFC and their contractors. Analysis approaches and their verification will be addressed. The Shuttle procedures are general in nature and apply to other than Shuttle space vehicles.					
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TABLE OF CONTENTS

	Page
I. INTRODUCTION	1
II. OVERALL APPROACH.....	1
III. SYSTEMS LOADS ANALYSIS	4
A. Approach	5
B. Verification	13
C. External Loads Output	14
IV. ELEMENT STRUCTURAL ANALYSIS	29
V. SUBELEMENT AND LOCAL ANALYSIS.....	39
VI. SUMMARY	48
REFERENCES	50

LIST OF ILLUSTRATIONS

Figure	Title	Page
1.	Structural analysis	2
2.	Shuttle level II criteria management flow	3
3.	Loads analysis flow	6
4.	Structural analysis iterative flow	7
5.	Parameter variations for loads analysis.....	8
6.	Parameter variations for loads analysis.....	9
7.	Parameter variations for loads analysis.....	10
8.	SRB load indicator, aft attach	11
9.	ET load indicator, hydrogen barrel panel	12
10.	Major integrated ground test	15
11.	Major integrated ground test	16
12.	Major integrated ground test	17
13.	Strut load comparison	18
14.	Strut and holddown post load comparison	19
15.	Force and moment SRM interface load comparison.....	20
16.	Force and moment SRM interface load comparison.....	21
17.	Force and moment SRM buildup case loads	22
18.	Force and moment SRM liftoff case loads	23
19.	ET schematic with strut forces	24
20.	P10 strut load predicted to flight liftoff	25
21.	P10 strut load predicted to flight Max Q	26
22.	P13 strut load predicted to flight Max Q	27
23.	Shuttle liftoff transient loads	28
24.	Shear distribution	30
25.	Moment distribution.....	31

LIST OF ILLUSTRATIONS (Concluded)

Figure	Title	Page
26.	Liftoff loads comparison IVBC-2 and IVBC-3	32
27.	Max Q loads comparison IVBC-2 and IVBC-3	33
28.	SRB transient and max-min loads	35
29.	SRB design load events	36
30.	SRM case stress summary.....	37
31.	SRB/SRM stress distribution.....	38
32.	The finite element method	40
33.	The finite element general concept.....	41
34.	The finite element basic concept	42
35.	The finite element general approach	43
36.	SRM field joint response, liftoff	45
37.	SRM field joint response, Max Q	46
38.	SRB aft skirt stress distribution	47

TECHNICAL MEMORANDUM

STRUCTURAL MARGINS ASSESSMENT APPROACH

I. INTRODUCTION

Various approaches exist for determining structural loads and the resulting structural margins. These margins are stated as stability, safety factors on ultimate and yield stresses, fracture limits, fatigue lifetime, reuse criteria, operations, etc. Regardless of the techniques chosen, consistent and compatible approaches must be used starting with the system loads and continuing through the element analysis and on to the smallest section evaluated. The purpose of this document is to outline this consistent approach as used by Marshall Space Flight Center (MSFC) and applied to the Shuttle projects. First, system analysis will be discussed, followed by a discussion of how this consistent set of data and analyses is carried through to the smallest element section. Also discussed will be the philosophy or criteria used to determine model and analysis detail at each structural level. Analysis verification approaches and philosophy are included. This document does not replace the NASA design documents [1,5-12], but serves as an augmentation of them.

II. OVERALL APPROACH

The approach chosen for structural design and verification must be comprehensive, consistent, and focused. Therefore, it is necessary that common models, environment data bases, analysis approaches, and criteria be employed by all vehicle or system elements to insure a compatible system risks assessment. The assurance that this happens involves proper organization and control (management). This paper will discuss the analysis and test approaches and their management leaving the other areas to separate documentation.

Up front, the basic problem facing structural analysis and verification should be clearly stated. The problem: All analyses are simulations which are not complete (limited) which attempt to predict trends and what will happen. In other words, models are models, not exact representations of physical law but are mathematical assumptions of these laws. The number and kind of assumptions determine the degree of replication. Hardware testing in general does not duplicate flight experience, since usually it is ground test of partial systems. Test constraints, etc., place the limitations as assumptions do in analysis. How we put these pieces together determines the validity of the design.

The basic concept and philosophy of this approach are shown on Figure 1. The process starts with each element and its subelements providing the structural models and all pertinent parametric data (example: SRB thrust, thrust rise rate, pressure) to the integration contractor for the system loads analysis. These models must be compatible with all other element models and with the final element stress analysis models. This compatibility for the Space Shuttle is assured by various management and review techniques. This is accomplished by the Loads Panel, the Performance Panel, the Ascent Flight Systems Integration Group (AFSIG), and the Systems Integration Review (SIR) (Fig. 2). Notice the hierarchal decision arrangement. The AFSIG and the Panels reporting to it are technical review and recommending bodies

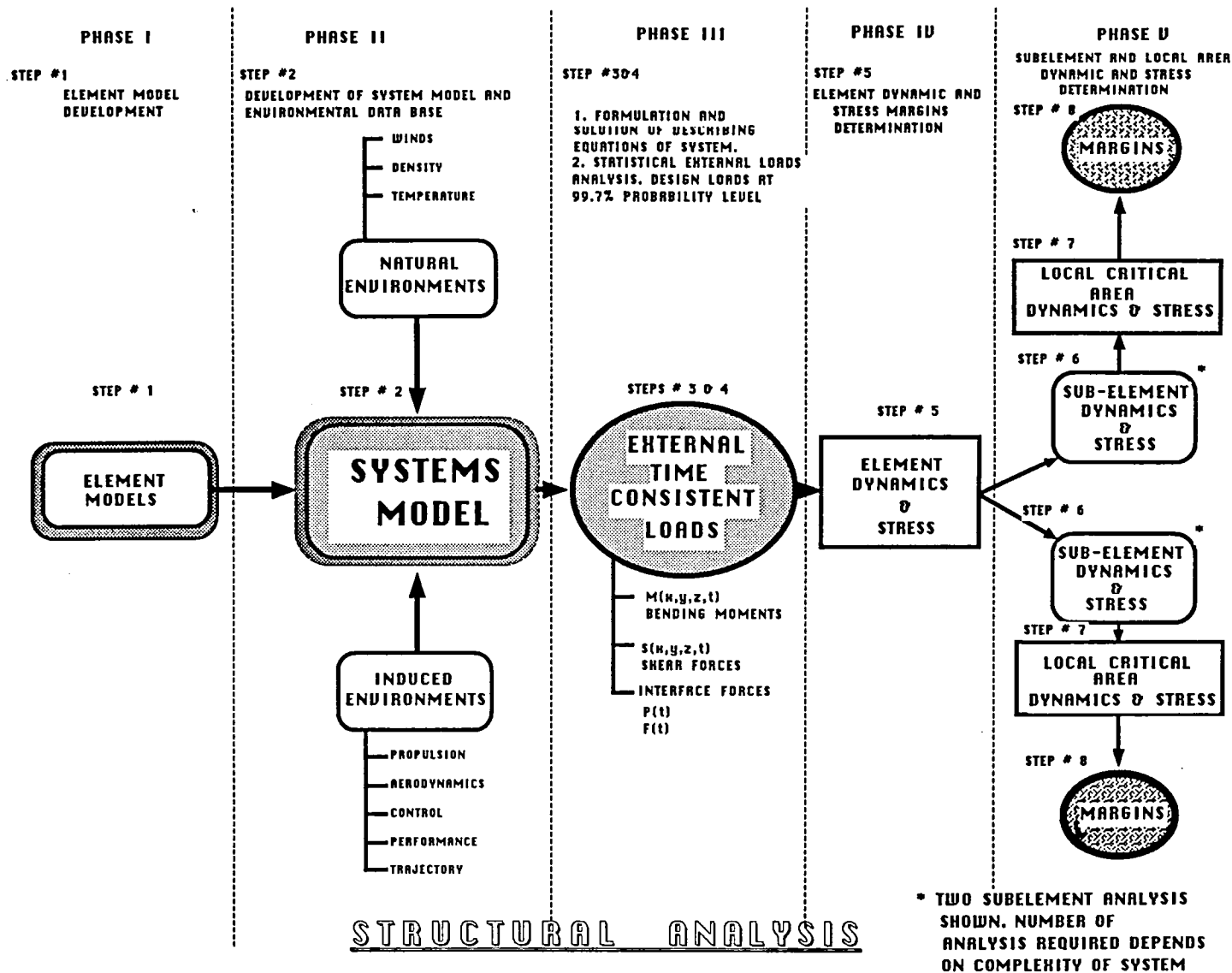


Figure 1. Structural analysis.

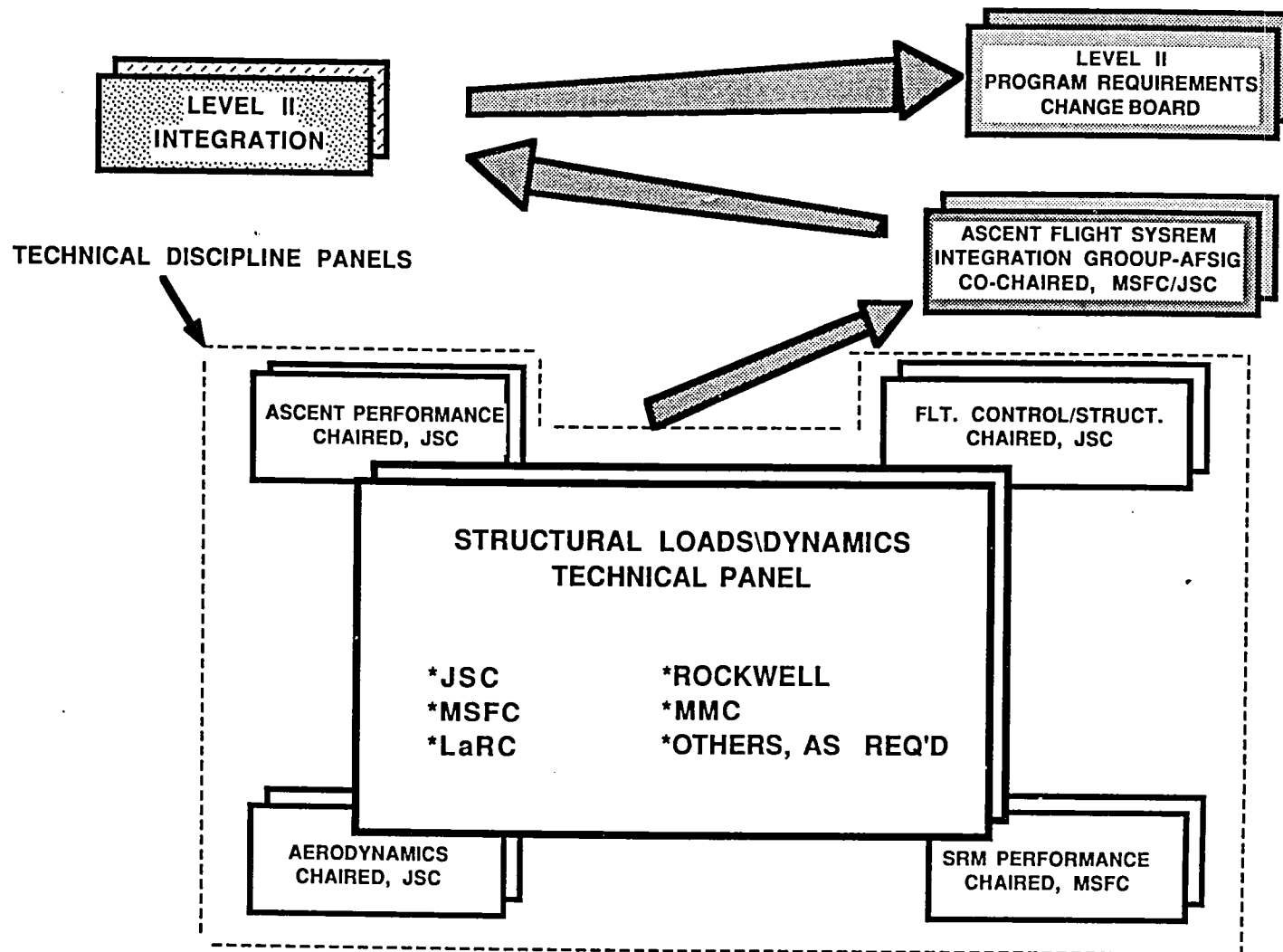


Figure 2. Shuttle level II criteria management flow.

and are not project decision arms. This helps to insure unbiased penetration without constraints, making only technical recommendations, leaving the risk decision to others. The system integration approach, parameter variations, statistical criteria, and verification required are worked through the same groups. Using these criteria, loads analysis for each design condition (parameter combinations with natural environments) are to be conducted and loads outputted. Figure 1 also shows some of the natural and induced environments used to determine the loads. These analyses are made in a statistical manner such that the resulting responses (loads, etc.) are at a 99.7 percent probability level of occurrence when varying all system parameters and environment values within the expected range. Included are all vehicle parameters and natural environments, such as wind speed, wind shears, and wind gust. Individual parameter variations will not necessarily be at the 3-sigma level, but the resulting variations produce a 3-sigma combined statistical response. For example, a 3-sigma response would not have individual 3-sigma wind speed, shear, and gust in combination, but would be a 3-sigma response using the individual probabilities (distribution) of these wind parameters. This response can be accomplished in the response analysis using such techniques as Monte Carlo, or on the environment side, by creating a combined 3-sigma wind environment. The loads are output as bending moments $[M_x(t), M_y(t), M_z(t)]$, shears $[S_x(t), S_y(t), S_z(t)]$, and interface forces where applicable, $P_i(x, y, z, t)$. Vehicle stations for these outputs are determined by the elements needs and integration requirements.

Using the appropriate sets of operational interface and external loads on each element, the structural margins are determined. Phase IV starts with a more detailed model (than the one used in system loads analysis) in conjunction with the interface and external forces from the system analysis. This step provides general structural capability plus the interface forces for conducting subelement responses. The subelement response which follows provides more detailed structural capability by using a still higher fidelity model. In addition, this subelement analysis provides the interface forces for a detailed linear and nonlinear analysis of any substructure that requires special considerations or shows low margins. This is to be accomplished using very fine grained models in conjunction with special codes and analysis techniques. It should be clear from this general approach discussion that models, response data, input data, etc., must be consistent and compatible to insure proper results. The following sections discuss the details of each of the steps and provide some typical examples.

It should be pointed out at this time that throughout each of these phases, two major principles or procedures must be adhered to: (1) conduct sensitivity studies to the level that a good understanding exists for all interactions and that key parameters are understood, and (2) conduct simplified hand analyses including free body diagrams, flows, schematics, etc., so that the phenomenon is clearly understood. This insight also serves as a guide to the more comprehensive studies. Computational and testing techniques have become so sophisticated that without these guides, serious errors will be made. Remember, all computer models, analyses, etc., are models and only as good as the assumptions used.

III. SYSTEMS LOADS ANALYSIS

Systems external loads analysis approaches are treated extensively in References 2 and 3. This section will highlight the key elements found in these references and in special presentations made over the years. Together these constitute the basic

approach to calculating systems loads. The system loads analysis must use models for each element that are of proper detail and characteristics to predict systems interaction and to account for the accurate loads distribution and all element-to-element forces. This means that all element-to-element interface structures and back-up structures are correctly accounted for in the system analysis and that these forces are output properly. Figure 3 shows how these interaction studies are conducted. Included in this figure, besides the models, are the additional interactions between environments, performance, loads, and verification. The solid arrows show the interactive analysis portion. The open arrows show the verification. This interaction is depicted for the loads analysis on Figure 4 by showing conceptually how the data flow occurs for the different phases of the margins assessment. This chart is a more detailed depiction of the loads and stress portion of Figure 1 showing how use is made of interdisciplinary analysis. Notice the strong interactive loops depicted by the double lines. Notice that the major outputs are ultimate and yield margins of safety, fracture mechanics/NDI, fatigue (lifetime), stability, and responses.

A. Approach

The approach used to generate Space Shuttle loads will now be elaborated on for the liftoff regime in order to make the external loads analysis process clearly understood. The first step (Fig. 1) utilizes test-verified dynamic models of each element (SRB, ET, SSME, Orbiter, Payload, MLP). These models are coupled together using proper interface models in conjunction with either substructuring or modal coupling techniques. This step produces an overall vehicle dynamic model containing up to 300 modes with frequencies through 50 Hz. Step 2 takes this complicated dynamic model and descriptions of all known forces and formulates a set of describing differential equations, which when integrated time-wise, will describe the dynamic characteristics of any point on the Shuttle structure. Various methods can be used to develop this set of equations; however, the Lagrange equations are usually used by selecting sets of generalized coordinates. This allows writing the kinetic and potential energy functions, dissipation functions, and, through virtual work, the generalized forces. Integration of the resulting equations, using either digital or hybrid computers, produces the responses and external loads (step 3). Since generalized forces are not precisely known (i.e., only known to a test-verified statistical level), a discrete loads case will not describe the design loads. Step 4 consists of running many cases of loads determined by taking different combinations of the possible variations in generalized forces. Since different parts of the structure will show higher loads for different parameter combinations, enough cases must be run to maximize loads for all critical structures. Figures 5 through 7 show the parameter set varied (generalized forces/parameters) for developing liftoff loads. Presently, it takes 27 cases to develop loads for all pertinent Shuttle structures. Therefore, the loads analysis progresses through this process by varying the vehicle and environmental parameters to obtain these 27 sets of 3-sigma loads response. As discussed in the overall section III, 3-sigma loads response is a vehicle structural load that has a 3-sigma probability of occurrence under all possible natural and induced environment combinations, not worse-on-worse combinations of 3-sigma levels of each parameter. One discrete loads case is not possible because different wind directions and other parameters maximize the load for different parts of the vehicle structure. In order to facilitate determination of these different cases, load and stress indicators of critical structural areas are utilized. Load indicators are algorithms that relate external loads to structural capability. Load and stress indicators should be developed early in a program and updated as required in order to simplify analysis and outputs. Two typical indicators are shown on Figures 8 and 9. These loads and stress indicators and/or transformation can be analytically determined as

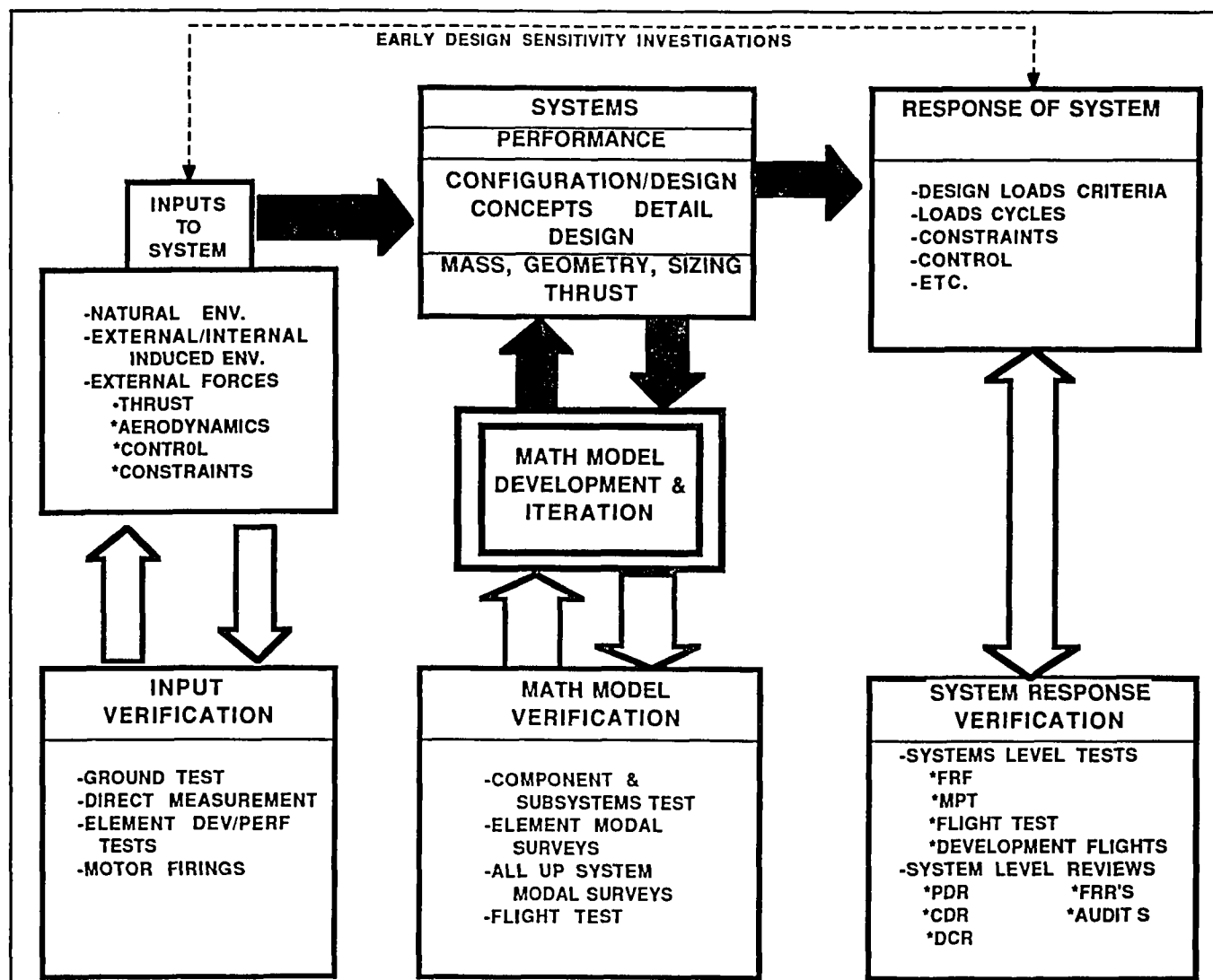
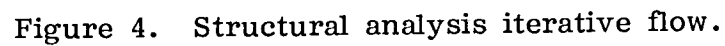


Figure 3. Loads analysis flow.



SRM PROPULSION

- TC227A-75 THRUST VS. TIME CURVE PER SE-019-083-2H (SRB SYSTEMS DATA BOOK) FOR MAX/MIN GRAIN TEMPERATUTES (TC227H I PROPOSED AS UPDATE)
- THRUST LEVEL DEVELOPMENT UNCERTAINTY
- STEADY-STATE THRUST MISMATCH BETWEEN SRM'S
- FLIGHT-TO-FLIGHT THRUST LEVEL UNCERTAINTY
- THRUST BUILDUP RATE DEVELOPMENT UNCERTAINTY
- THRUST MISALIGNMENT

ANALYSIS TOLERANCE

{ 90° F (ETR)
40° F (WTR)

± 3%

35,000 LBS.

{ ± 5% SINGLE MOTOR
± 4.9% BOTH MOTORS

REF: SDIL SRM76-037

± 0.50% (BOTH); 0.707° (ONE)

AERODYNAMICS

- GROUND WIND DRAG COEFFICIENTS PER SD72-SH-0060-2 (MATED VEHICLE AERO DESIGN DATA BOOK) AND ROCKWELL INTERNAL LETTER SAS/AERO/75-430

NONE

MAIN PROPULSION

- 3 SSME'S AT 100% THRUST (RPL) TO 109% THRUST (RPL)

NONE

Figure 5. Parameter variations for loads analysis.

MASS PROPERTIES

- MINIMUM PAYLOAD OF 2,500 LBS. (MISSION 3B)
- MAXIMUM PAYLOAD OF 32,000 LBS. (MISSION 3A)
- MAXIMUM PAYLOAD OF 65,000 LBS. (MISSION 3A)

ANALYSIS TOLERANCE

NONE
NONE
NONE

MISCELLANEOUS

- SRB/MLP HOLDDOWN BOLT PRELOAD (750,000 LBS)

NONE

FLIGHT CONTROL AND GUIDANCE

- ROCKWELL CONTROL NO. 7 PER SD73-SH-0047-1
(INTEGRATED VEHICLE FLIGHT CONTROL SYSTEM
DATA BOOK)
- ALL NOZZLES GIMBAL BUT SRB NOZZLE GIMBAL
LIMITED TO 2° FOR FIRST 5 SECONDS
- SRB MISTRIM TO 0° UNTIL SSV CLEARS THE LAUNCH
PEDESTAL
- STB TVC MISALIGNMENT

NONE

$\left\{ \begin{array}{l} \pm 0.17^\circ \text{ (SRB)} \\ \pm 0.23^\circ \text{ (SSME)} \end{array} \right.$

NONE

2 σ RSS EACH SRB IN
WORST DIRECTION

EXTERNAL ENVIRONMENT

- 95% WIND SPEED (ONE HOUR EXPOSURE)
- PEAK WIND SPEED
- TUNED GUST (WORST CASE)

NONE

24 KNOTS (MAX)

NONE

VEHICLE DYNAMICS

- FIRST 50 BENDING MODES WITH 1% DAMPING

ANALYSIS TOLERANCE

NONE

FAILURE MODELS

- NONE

ANALYTICAL APPROACH

- DIGITAL SIMULATION OF VEHICLE FLEXIBLE BODY RESPONSE DUE TO APPLIED FORCES AND RELEASE OF BASE CONSTRAINTS

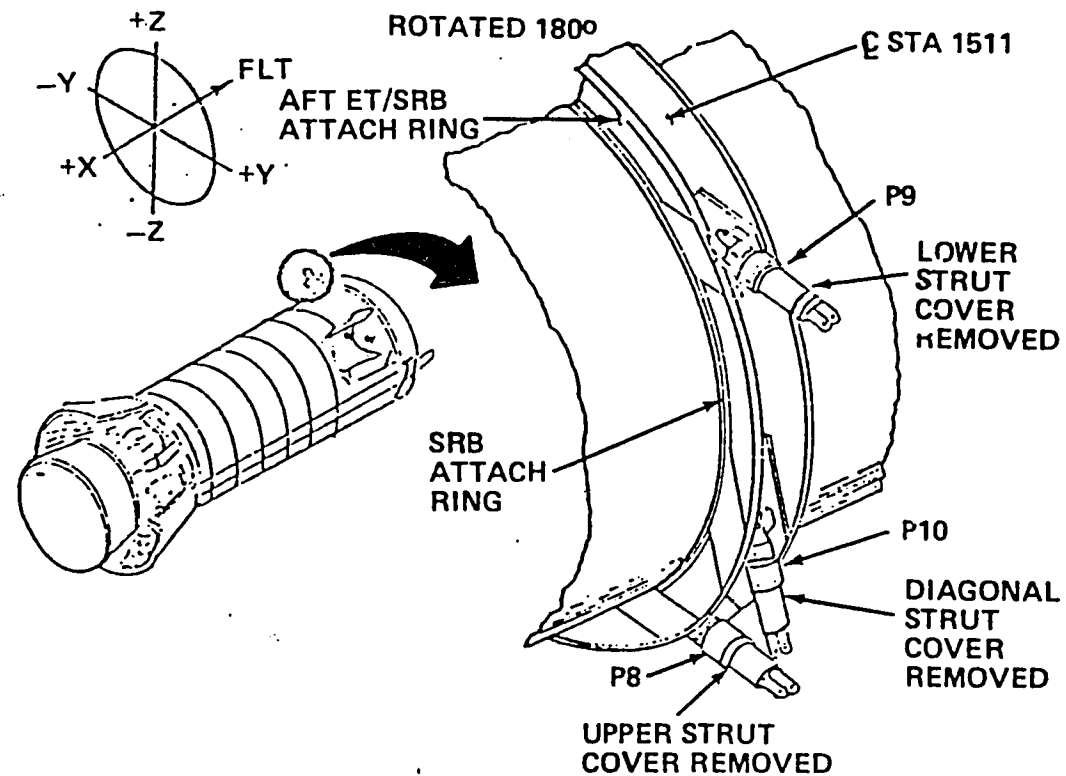
COMBINATION METHOD

- SEQUENCE OF EVENTS SELECTED OR MAX LOADS (WOW)
- RSS SIMILAR UNCERTAINTIES AS A GROUP THEN ADD GROUPS ($\pm 2\sigma$ DEVIATIONS) IN WORST-ON-WORST COMBINATION

DOCUMENTATION OF RESULTS

- SD73-SH-0069-1, -2, -3, AND -4 STRUCTURAL DESIGN LOADS DATA BOOK

Figure 7. Parameter variations for loads analysis.



VEHICLE MOMENT (CLOCKWISE) LOOKING AFT ON VEHICLE.

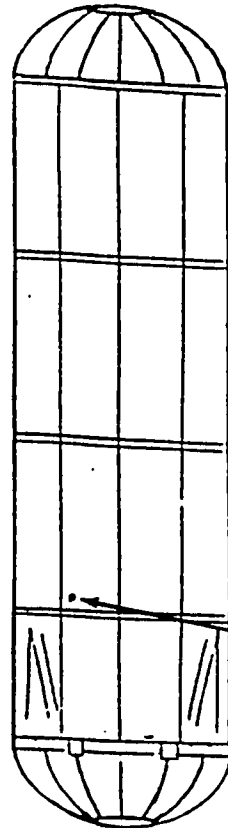
$$\text{MAX. MOMENT} = 28945 \times 10^3 \geq -P8 (57.0) + P9 (57.0) + P10 (68.34)$$

NOTE: NO MOMENT CAN EXCEED THIS VALUE FOR ANY CONDITION.

CRITICAL AREA	
FAILURE MODE	

Figure 8. SRB load indicator, aft attach.

LOAD INDICATOR EQUATION L3-42



$$22535.3F_X 1871 + 8.1452 M_Y 1871 + 108.19 M_Z 1871 - 11821 F.T07 \leq 10^7$$

EFFECTIVITY () DESIGN CONDITION	PL	LO	HQ	BA	PR	(PO)	OA	OE
		X	X					
CRITICAL AREA	BARREL PANEL 0 = 43° STATION 1859							
FAILURE MODE	STABILITY		STRENGTH			OTHER		
	AT ULT. LOAD							
FACTOR OF SAFETY	INDICATOR		ANALYSIS			TEST DEMON.		
	1.53		1.53			1.76		
INDICATOR ERROR 0%				EFFECTIVITY COND S.F. = 1.33				

Figure 9. ET load indicator, hydrogen barrel panel.

part of determining dynamic and stress models or by curve fitting stress analysis results as a function of key parameters (see later section). Using these indicators and other design criteria, design loads cases are run for each of the Shuttle operational flight events. These Shuttle operational events include:

- Transportation
- Assembly
- On-pad (including VAB to pad move)
- Liftoff (SSME ignition through liftoff transient)
- Max Q
- High g
- Reentry (SRB and Orbiter)
- Water impact (SRB)
- Towing SRB
- Landing (Orbiter and payloads)
- SRB separation
- ET separation

The more important parameters to be varied in order to provide the sets of 3-sigma loads are:

- 1) Control (gimbal angle, gimbal rates, vehicle acceleration, vehicle rates, angle of attack, etc.).
- 2) Propulsion (thrust, thrust rise rate, pressure, etc.).
- 3) Winds (speed, shear, gusts, and direction).
- 4) Cryo (thermal).
- 5) Trajectories (load relief, launch azimuth, orbit, payload).
- 6) Inertia.
- 7) Mass.
- 8) Configuration (geometric offsets, shapes, etc.).
- 9) Aerodynamics.
- 10) Payload variations.
- 11) Mission variations.

B. Verification

It is mandatory that for each parameter used, a verified statistical distribution, including the 3-sigma level, be determined and input into the analysis. Any appropriate parameter variation, sensitivity analysis, statistical combination such as Monte Carlo, RSS'ing, etc., can be used to generate the loads data.

The structural models must be verified by dynamic and static tests preferably of full-scale hardware. With proper attention, scale testing is acceptable. All testing must be preceded by a pre-test analysis, guiding the test conditions, instrumentation

location, and test approaches. A post-test model update is required, based on the correlation of model and test data, to provide a basis for assessing changes, manufacturing discrepancies, etc., and, particularly, to predict with confidence criteria for operational conditions which were not directly verified by test.

Verification of input parameters is accomplished through tests of various types, such as wind tunnel, propulsion system firing, etc. Pre-test analyses are required for guiding test definition, instrumentation, etc., with post-test updates providing the final data sets.

The past Space Shuttle configuration was verified in this manner. Figures 10 through 12 are the summary of some of the key verification tests.

All significant design changes are verified and loads analyses reconducted.

The final verification of any system is accomplished through development flights, highly instrumented at critical areas, for loads and environment correlations to flight load predictions and design loads. Six of the first seven Shuttle flights carried this instrumentation. Results are shown in Figures 13 through 18 as examples of this verification approach. Figure 19 is a schematic of the ET showing strut or interface force nomenclature for Orbiter-to-tank and tank-to-SRB. This is given as reference for data identification presented in Figures 13 and 14. These tables show the measured in-flight load percentage of design load for the interface forces for all flight events for flights STS-1 through -7. Notice that all loads were well within design, except for the bolt loads. It has since been determined that these are not load exceedances but calibration errors. Figures 15 through 18 give SRB forces and moments at several vehicle stations for SSME buildup and liftoff. Compared to design loads for that event, these loads are as expected. The event shown may not be the design event and hence the load is low.

The final verification is obtained by correlating actual flight predicted time responses to the measured flight data. Figure 20 is the comparison of strut P10 for ST-5 of predicted versus measured for the liftoff event. Predicted loads are higher than measured but contain the same trends and frequency content indicating good analytical approaches. Figures 21 and 22 are similar comparisons for struts P10 and P13 for the max q flight event. Excellent agreement is shown between predicted and measured parameters. Rockwell, Space Division, conducted and is the source of these analysis comparisons to flight.

C. External Loads Output

The 3-sigma load sets are obtained by the techniques just described, output in format and locations required by the elements for margin assessment. In general, these loads will be output as a time consistent set of loads at each prescribed station as:

Shear forces (x, y, z, t)
Moments (x, y, z, t)
Interface forces (x, y, z, t)

Figure 23 is a typical example of this type of output for Shuttle during SSME buildup through the liftoff transient. Depicted in the center is the Shuttle vehicle. On the left is one example of the many input forces used concurrently; other typical

●1/4-SCALE GROUND VIBRATION TESTING (QSGVT)

- THE INDIVIDUAL ELEMENT MODAL VIBRATION TESTS OF THE EMPTY SRB'S, FULL SRB'S, EXTERNAL TANK (ET), AND ORBITER (ORB) HAVE BEEN COMPLETED. THE FIRST MATED TEST WITH THE ET AND ORBITER STARTED JUNE 15, 1977 AND WAS COMPLETED JULY 31, 1977. THE ORB/ET/SRB LIFT-OFF CONDITION TESTS STARTED AUGUST 1, 1977 AND WERE COMPLETED SEPT. 21, 1977. ALL 1/4-SCALE MODAL VIBRATION TESTING WAS COMPLETED BY DECEMBER 1977. INFLUENCE COEFFICIENT TESTS (I/C) WERE COMPLETED ON THE EMPTY SRB AND ET. THE I/C TESTS ON THE FULL OR LIFT-OFF CONDITION SRB WAS CONDUCTED IN JANUARY AND FEBRUARY 1978.

●MATED VERTICAL GROUND VIBRATION TEST (MVGVT)

- MVGVT TEST USING THE EXISTING SATURN DYNAMIC FACILITY SYSTEMS AND COMPONENTS STARTED IN MAY 1978 AND WAS COMPLETED IN NOV. 1978.

<u>TEST AND LOCATION</u>	<u>CONFIGURATION</u>	<u>PURPOSE</u>
● UMBILICAL SYSTEMS VERIFICATIONS (LETF) (KSC)	FLIGHT TO GROUND UMBILICALS WITH ASSOCIATED FLIGHT VEHICLE SKIN PANELS AND GROUND SYSTEMS. (i.e., SWING ARMS, TAIL SERVICE MASTS)	VERIFY GROUND TO FLIGHT INTERFACES IN PERFORMANCE AND COMPATIBILITY AREAS PRIOR TO MOF
● STRUCTURAL TEST ARTICLE (ET) (MSFC)	LO ₂ TANK, LH ₂ TANK AND INTER TANK	VERIFY THE STRENGTH INTEGRITY OF THE PRIMARY LOAD CARRYING STRUCTURE
● STRUCTURAL STATIC/FATIGUE (ORBITER) (PALMDALE)	AIRFRAME STRUCTURE INCLUDING ALL PRIMARY AND SELECTED SECONDARY STRUCTURE. GENERALLY, NO SYSTEMS	VERIFY STRUCTURAL INTEGRITY FOR: LIMIT AND ULTIMATE LOADS AND 160 MISSION LIFE X SCATTER FACTOR OF 4
● STATIC STRUCTURAL TEST (SRB) (MSFC)	SRB SHORT STACK CONFIGURATION, STRUCTURALLY FLIGHT TYPE VEHICLE WITH FOUR CENTER MOTOR SEGMENTS ELIMINATED	VERIFY STRUCTURAL INTEGRITY FOR CRITICAL DESIGN LIMIT AND ULTIMATE LOADS AND THE NORMAL SERVICE LIFE
● FWD RCS STATIC FIRINGS (WSTF)	SHALL CONSIST OF STRUCTURE AND COMPONENTS FUNCTIONALLY CONFIGURED TO REPRESENT THE FLIGHT ARTICLE	DEMONSTRATE THE RCS PERFORMANCE

Figure 11. Major integrated ground test.

<u>TEST AND LOCATION</u>	<u>CONFIGURATION</u>	<u>PURPOSE</u>
● MPTA (NSTL)	3 MAIN ENGINES + FLIGHT WEIGHT EXTERNAL TANK + FLIGHT WEIGHT AFT FUSELAGE, INTERFACE SECTION AND A BOILERPLATE MID/FWD FUSELAGE TRUSS STRUCTURE	VERIFY MPS PERFORMANCE AND COMPATIBILITY WITH INTERFACING ELEMENTS AND SUBSYSTEM
● OMS/RCS STATIC FIRINGS (WSTF)	CONSISTED OF FLIGHT WEIGHT PRIMARY AND SECONDARY STRUCTURE, FLIGHT WEIGHT QUALIFIABLE COMPONENTS FUNCTIONALLY CONFIGURED TO REPRESENT THE FLIGHT ARTICLE	DEMONSTRATE OMS, RCS PERFORMANCE
● ECLSS (JSC)	BOILERPLATE TEST ARTICLE. COMPLETE ECLSS, PARTIAL AVIONICS, CREW EQUIPMENT, AIRLOCK	VERIFY ECLSS INTEGRATED OPS AND PERFORM MANRATING OF ECLSS FOR FVF (8 PSI). VERIFY AIRLOCK PERFORMANCE
● FLIGHT READINESS FIRING (KSC)	FIRST SHUTTLE VEHICLE — OV-102 — FLIGHT EXTERNAL TANK — FLIGHT SRB'S	PERFORM UNMANNED SSME FIRING AT COMPLETION OF THE FIRST WET COUNTDOWN DEMONSTRATION TEST. FINAL VERIFICATION OF FLIGHT AND GROUND SYSTEMS PRIOR TO FMOF. PERFORMED ONE TIME ONLY

Figure 12. Major integrated ground test.

LOADS COMPARISON IN % OF DESIGN

STRUCTURE	STS-1 % EVENT	STS-2 % EVENT	STS-3 % EVENT	STS-4 % EVENT	STS-5 % EVENT	STS-7 % EVENT
P ₁	52 (LO)	44 (PO)	45 (PO)	43 (PO)	44 (PR)	44 (PR)
P ₂	50 (LO)	42 (PO)	41 (PO)	44 (PO)	42 (PR)	40 (PR)
P ₃	53 (PO)	55 (PO)	50 (PO)	54 (HQ)	58 (HQ)	57 (PR)
P ₄	53 (PO)	50 (PO)	56 (HQ)	56 (HQ)	52 (PR)	53 (PR)
P ₅	91 (PO)	87 (PO)	88 (PR)	88 (PR)	86 (PR)	93 (PR)
P ₆	88 (PO)	85 (PO)	88 (PR)	85 (PR)	88 (PR)	91 (PR)
P ₇	12 (HQ)	6 (PR)	18 (PR)	10 (PR)	8 (LO)	11 (PR)
CROSSBEAM	88 (BA)	88 (BA)	90 (BA)	91 (BA)	93 (BA)	92 (BA)
LO ₂ DOME	91 (LO)	92 (LO)	97 (LO)	78 (LO)	81 (LO)	—
Y RING	95 (LO)	96 (LO)	97 (LO)	81 (LO)	85 (LO)	—
LH ₂ DOME	96 (LO)	93 (LO)	83 (LO)	83 (LO)	—	—

LO — LIFTOFF
 HQ — MAX Q
 BA — MAX SRB ACCELERATION
 PR — PRE-SRB STAGING
 PO — POST SRB STAGING

Figure 13. Strut load comparison.

<u>LOADS COMPARISON IN % OF DESIGN</u>						
STRUCTURE	STS-1 % EVENT	STS-2 % EVENT	STS-3 % EVENT	STS-5 % EVENT	STS-6 % EVENT	STS-7 % EVENT
P ₈	28 (LO)	30 (LO)	25 (LO)	27 (LO)	25 (LO)	22 (LO)
P ₉	36 (LO)	32 (LO)	36 (LO)	31 (LO)	31 (LO)	31 (LO)
P ₁₀	49 (LO)	42 (LO)	34 (LO)	31 (LO)	34 (LO)	38 (LO)
P ₁₁	30 (LO)	25 (LO)	22 (HQ)	19 (LO)	28 (LO)	23 (LO)
P ₁₂	35 (LO)	35 (LO)	32 (LO)	30 (HQ)	30 (LO)	31 (LO)
P ₁₃	56 (LO)	45 (HQ)	36 (LO)	40 (HQ)	33 (LO)	35 (LO)
F _{B5} , F _{B6}	88 (BA)	88 (BA)	90 (BA)	93 (BA)	—	92 (BA)
AFT SKIRT — (ALL AT SSME BUILDUP)						
POST COMPRESSION	101	98	102	98	98	97
BOLT TENSION —		98	105	95	92	88
BASE MOMENT	96	104	104	94	95	92
LO — LIFTOFF						
HQ — MAX Q						
BA — MAX SRB ACCELERATION						

Figure 14. Strut and holddown post load comparison.

SSME BUILDUP
SRM CASE LOADS
RIGHT SRB

FORCE/ MOMENT	SRB STA. (IN)	PREDICTED NET LOAD (KIPS)	MEASURED NET LOAD					DESIGN LIMIT LOAD (KIPS)
			STS-1 (KIPS)	STS-2 (KIPS)	STS-3 (KIPS)	STS-5 (KIPS)	STS-6 (KIPS)	
F _x	611	—	260	835	405	237	565	420/1000 ⁽¹⁾
M _y **	611	—	— 39	— 30	— 38	— 35	— 41	— 34/5 ⁽¹⁾
F _x	1251	1070	1490	1085	995	1140	1253	1100/1690 ⁽¹⁾
M _y **	1251	— 144	— 183	— 187	— 173	— 184	— 191	— 180/22 ⁽¹⁾
F _x	1758	1490	1697	1687	1498	1747	1593	1540/2130 ⁽¹⁾
M _y **	1758	— 242	— 291	— 260	— 272	— 283	— 309	— 300/30 ⁽¹⁾
F _x	1935	1670	1823	1813	1624	1873	1719	1670/2220
M _y **	1935	—	— 332*	— 287*	— 307*	— 318	— 350	— 347/30

*NET MEASURED DATA — BASE LOADS EXTRAPOLATED FROM ABOVE LOADS

(1) DESIGNED BY EVENTS OTHER THAN SSME THRUST BUILDUP

**M_y GIVEN IN 10⁶ IN/LBS INSTEAD OF KIPS

M_y (10⁶ IN-LBS)

Figure 15. Force and moment SRM interface load comparison.

LIFTOFF
SRM CASE LOADS
RIGHT SRB

FORCE/ MOMENT	SRB STA. (IN)	PREDICTED NET LOAD (KIPS)	MEASURED NET LOAD					DESIGN LIMIT LOAD (KIPS)
			STS-1 (KIPS)	STS-2 (KIPS)	STS-3 (KIPS)	STS-5 (KIPS)	STS-6 (KIPS)	
F _x	611	-13,500/-9,000	-12,014	-11,287	-12,446	-11,434	-10,882	-14,300
M _y *	611	-20/20	-19	-25	-6	-34	-56	32
F _x	1251	-12,500/-8,700	-10,120	-9,883	-10,047	-9,613	-10,056	-13,200
M _y *	1251	-46/37	-22	-61	-3	-28	-30	-73
F _x	1758	-11,700/-8,200	-8,310	-8,444	-7,775	-7,803	-9,104	-12,400
M _y *	1758	-9/15	-14	-38	-14	-13	-38	23

*M_y GIVEN IN 10⁶ IN/LBS INSTEAD OF KIPS

Figure 16. Force and moment SRM interface load comparison.

SSME BUILDUP
SRM CASE LOADS
LEFT SRB

FORCE/ MOMENT	SRB STA. (IN)	PREDICTED NET LOAD (KIPS)	MEASURED NET LOAD					DESIGN LIMIT LOAD (KIPS)
			STS-1 (KIPS)	STS-2 (KIPS)	STS-3 (KIPS)	STS-5 (KIPS)	STS-6 (KIPS)	
F _x	611	—	—	—	—	—	—	420/1000 (1)
M _y **	611	—	—	—	—	—	—	—34/5 (1)
F _x	1251	1070	995	1002	1004	1090	789	1100/1690 (1)
M _y **	1251	— 144	— 181	— 181	— 173	— 170	— 212	— 180/22 (1)
F _x	1758	1490	1605	1770	1928	1945	1627	1540/2130 (1)
M _y **	1758	— 242	— 277	— 260	— 269	— 236	— 309	— 300/30 (1)
F _x	1935	1670	1823	1813	2054	2071	1753	1670/2220
M _y **	1935	—	— 332*	— 287*	— 303*	— 259*	— 350*	— 347/30
<p>*NET MEASURED DATA — BASE LOADS EXTRAPOLATED FROM ABOVE LOADS (1) DESIGNED BY EVENTS OTHER THAN SSME THRUST BUILDUP **M_y NOT GIVEN IN KIPS BUT IN (10⁶ IN-LBS)</p>								

Figure 17. Force and moment SRM buildup case loads.

**LIFTOFF
SRM CASE LOADS
LEFT SRB**

FORCE/ MOMENT	SRB STA. (IN)	PREDICTED NET LOAD (KIPS)	MEASURED NET LOAD					DESIGN LIMIT LOAD (KIPS)
			STS-1 (KIPS)	STS-2 (KIPS)	STS-3 (KIPS)	STS-5 (KIPS)	STS-6 (KIPS)	
F _x	611	-13,500/-9,400	-	-	-	-	-	-14,300
M _y *	611	-20/20	-	-	-	-	-	32
F _x	1251	-12,500/-8,700	-9,700	-10,005	-9,544	-9,353	-10,298	-13,200
M _y *	1251	-46/37	-28	-33	-45	-26	-27	-73
F _x	1758	-11,700/-8,200	-7,739	-7,502	-8,056	-6,685	-8,621	-12,400
M _y *	1758	-9/15	2	2	0	2	-22	23
*M _y GIVEN IN 10 ⁶ IN/LBS INSTEAD OF KIPS								

Figure 18. Force and moment SRM liftoff case loads.

TRUSS MEMBERS: P1 TO P13
 POSITIVE TENSION
 NEGATIVE COMPRESSION

ORTHOGONAL LOADS: P14 TO P19
 POSITIVE DIRECTIONS SHOWN

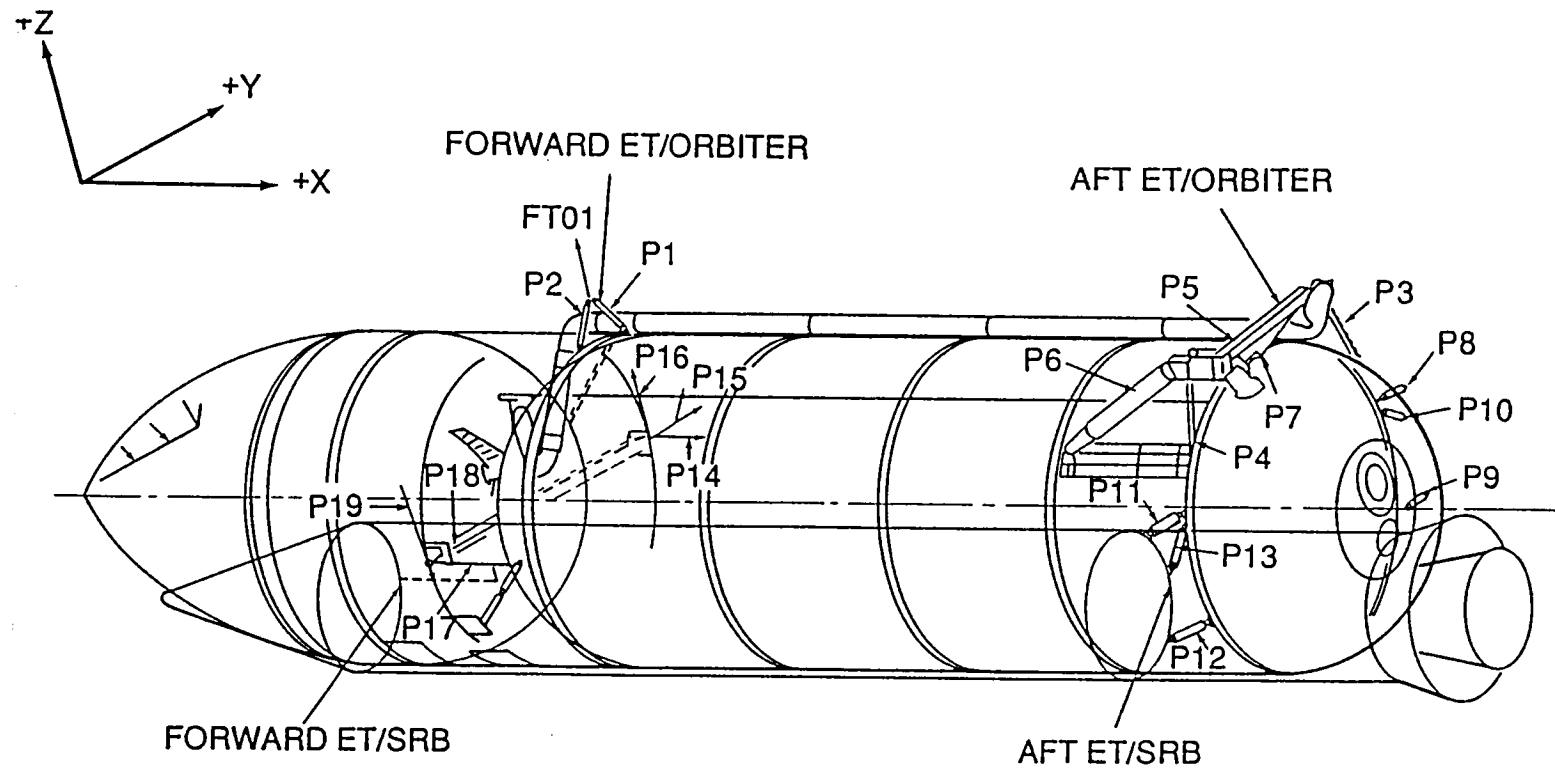


Figure 19. ET schematic with strut forces.

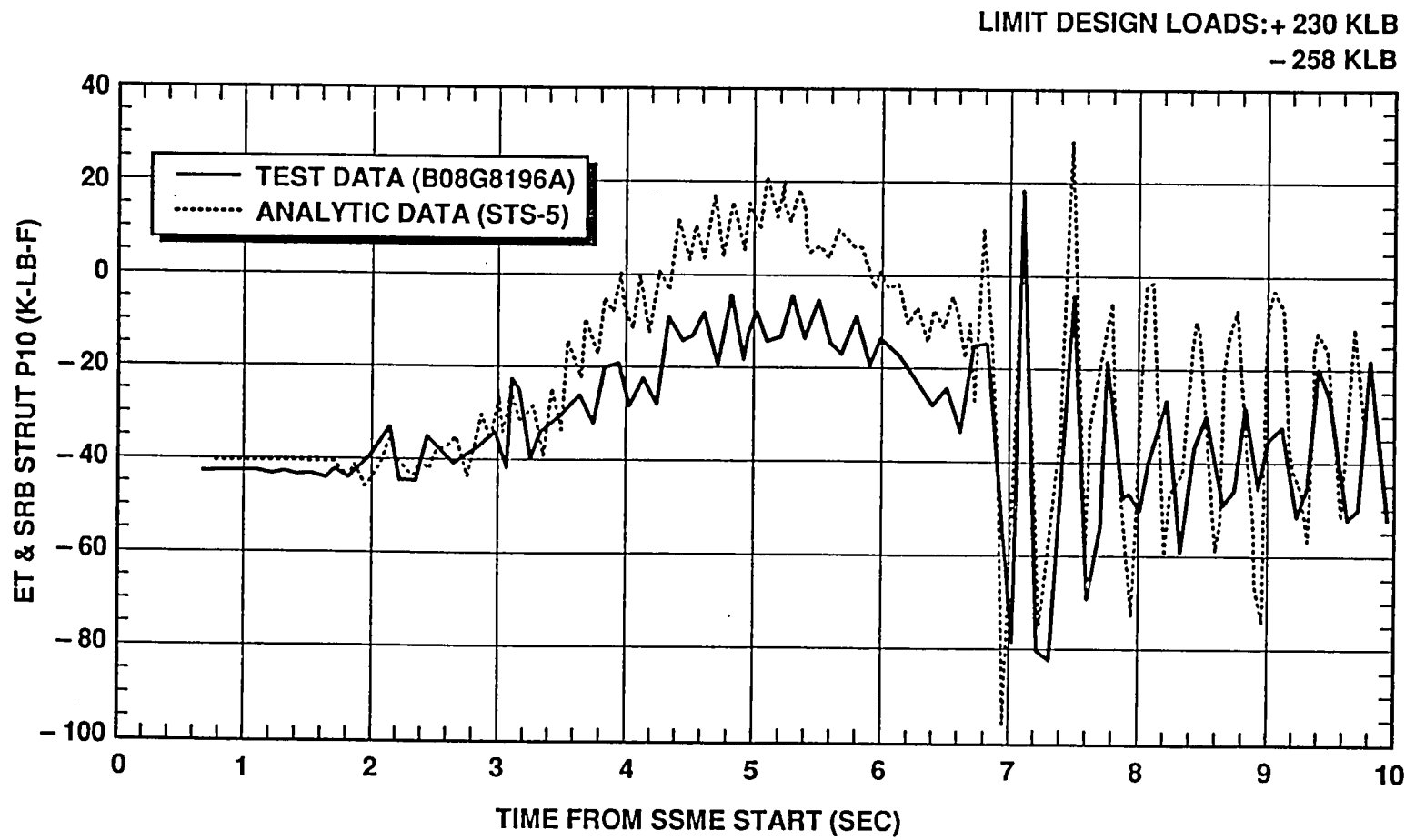


Figure 20. P10 strut load predicted to flight liftoff.

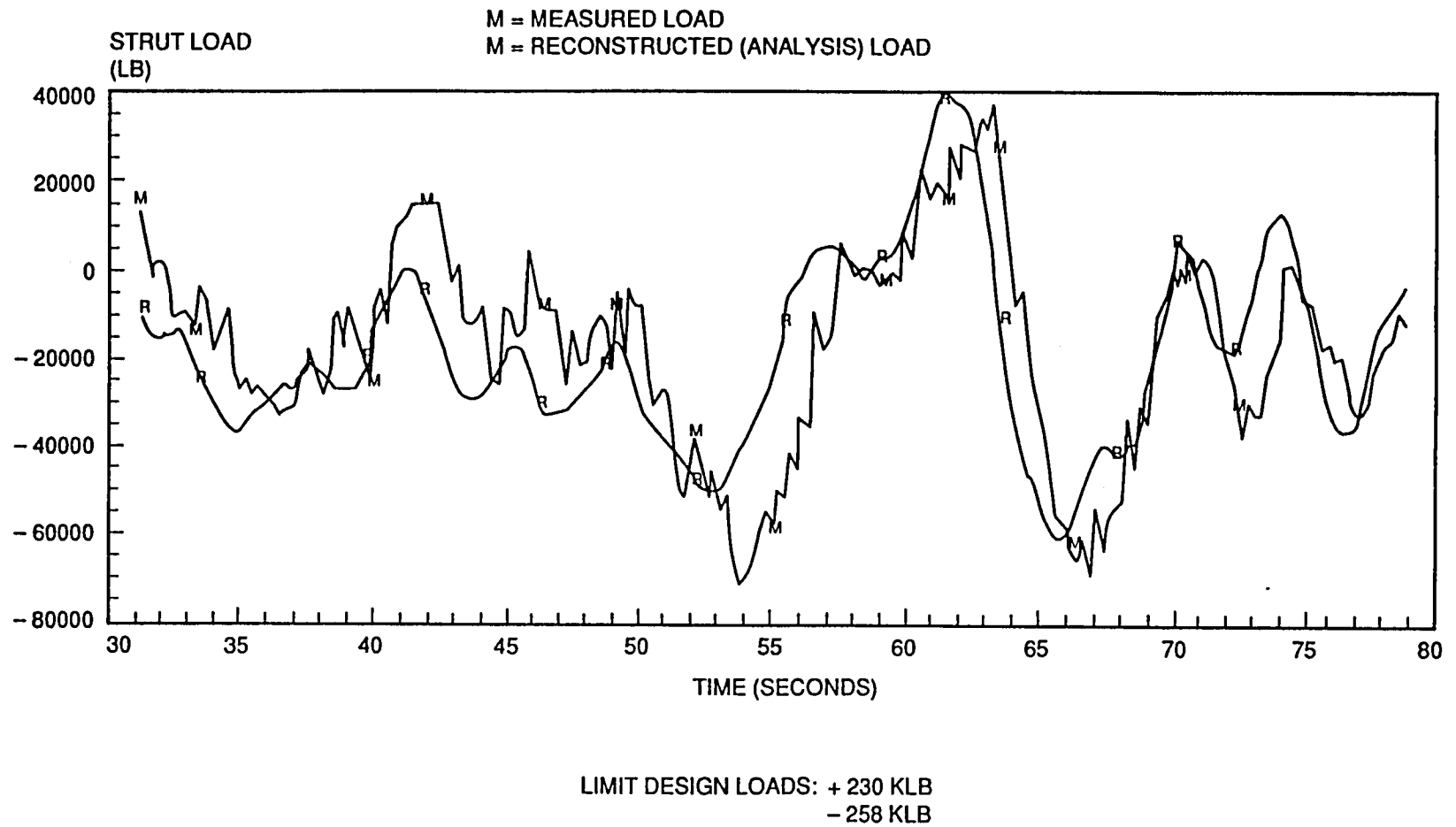


Figure 21. P10 strut load predicted to flight Max Q.

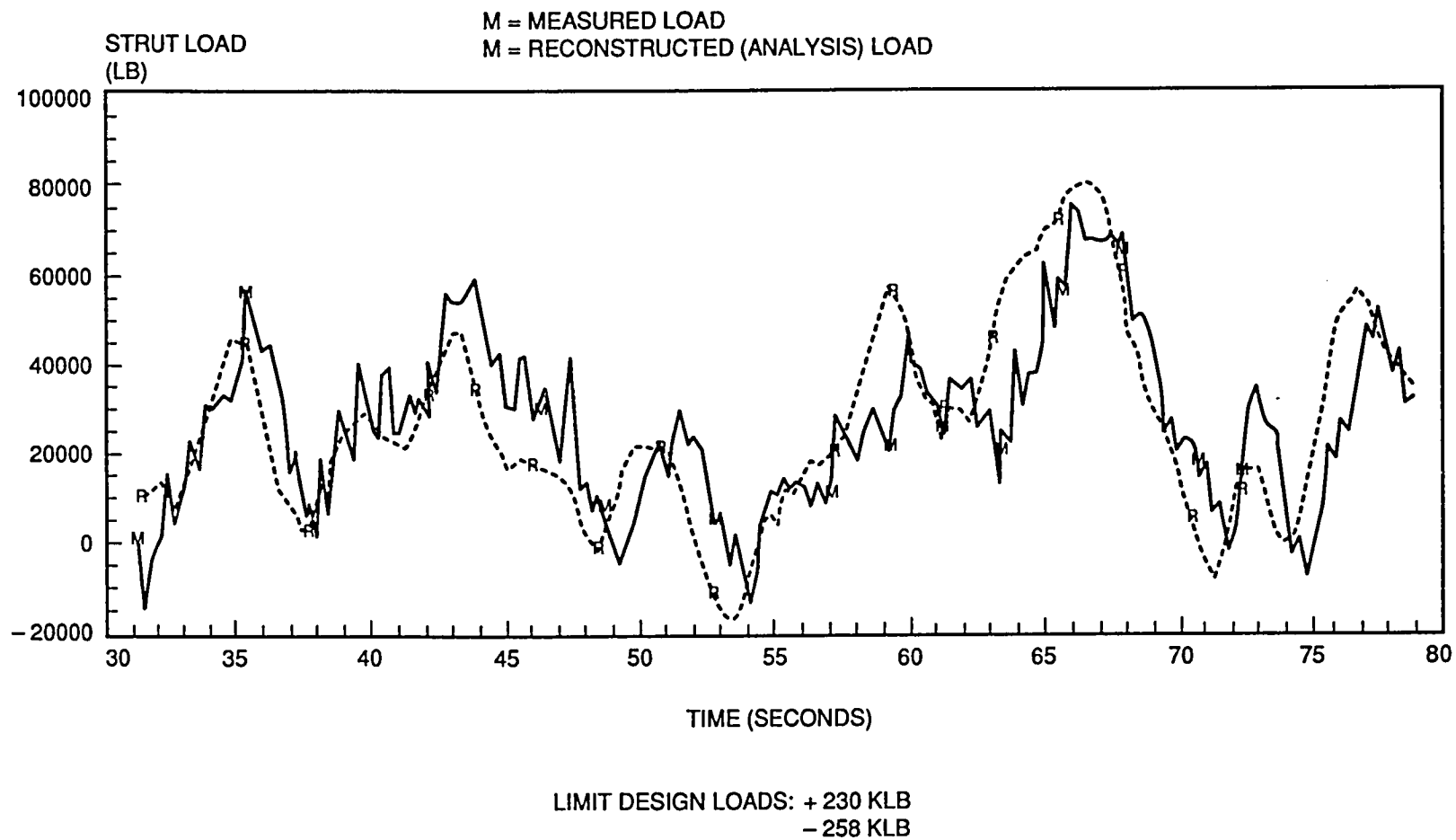


Figure 22. P13 strut load predicted to flight Max Q.

● FULL-SCALE TECHNIQUES

- REQUIRES SOLUTION OF THE COUPLED SHUTTLE/PAYLOAD SYSTEM (COUPLED LOADS ANALYSIS)

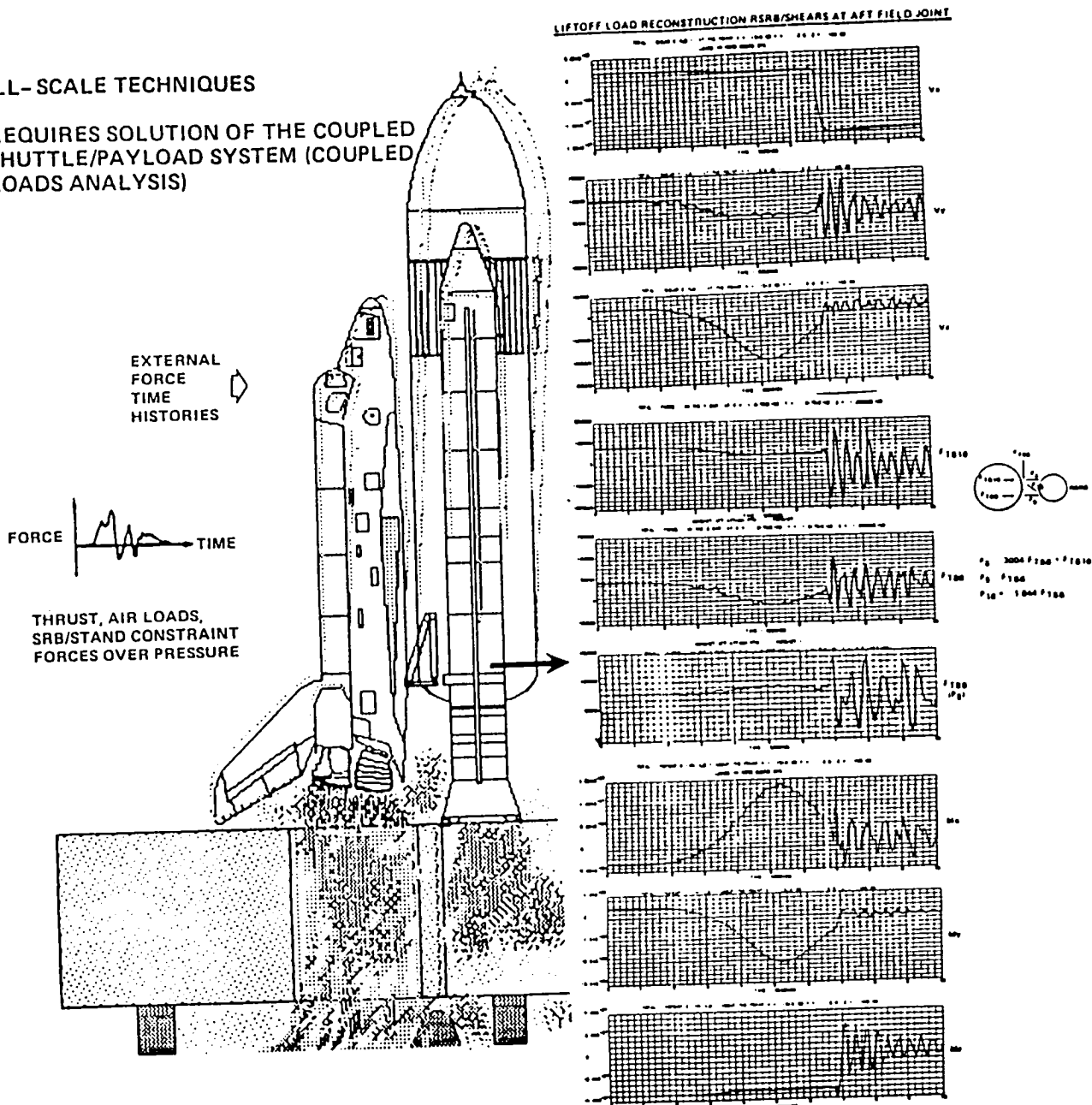


Figure 23. Shuttle liftoff transient loads.

forces are listed. On the right are the resulting time responses of the SRB at the ET attach ring station. Included are the three strut forces (interface forces), the three shear forces, and the three moments. Outputs of this form should be available for any vehicle station.

The large capacity of modern computers allows optimization of computer outputs at this point providing several options. Classically, the time consistent dynamic loads have been treated as quasi-static loads which are added to the static loads generated in a separate stress analysis. Now these two steps can be treated simultaneously if the dynamic model is compatible with the stress model (compatible node points, etc.). Using stress or loads transformations, the output of one analysis (loads) can drive the transformations producing time consistent stresses. This saves modeling time, allows less loads cases to produce 3-sigma conditions, and opens the door to a consistent Monte Carlo stress analysis not possible if the Monte Carlo is done on external loads. The Monte Carlo approach produces a more realistic representation of all parameters than the other approaches used, such as A-factor. As programs mature, load indications can be used in the same manner. The classical approach is still desirable in many cases, therefore, an alternate means of handling this is also available.

The peak values (time consistent sets) for all stations should be combined to provide running load distributions for static analysis. Figures 24 and 25 show typical shear and moment distributions developed for Shuttle design. There must be as many sets of these distributions as there are load sets and flight event analyses. Time consistency must be maintained as a general rule.

The purpose of this document is to delineate procedures and approaches; however, it should be mentioned that as a result of the knowledge of the first 25 Shuttle flights, a new loads analysis is underway. The reanalysis is defined as IVBC-3. The original final verification analysis was defined as IVBC-2. In general, this reanalysis has resulted in lower loads as can be seen on Figures 26 and 27 for the liftoff and max q flight regimes.

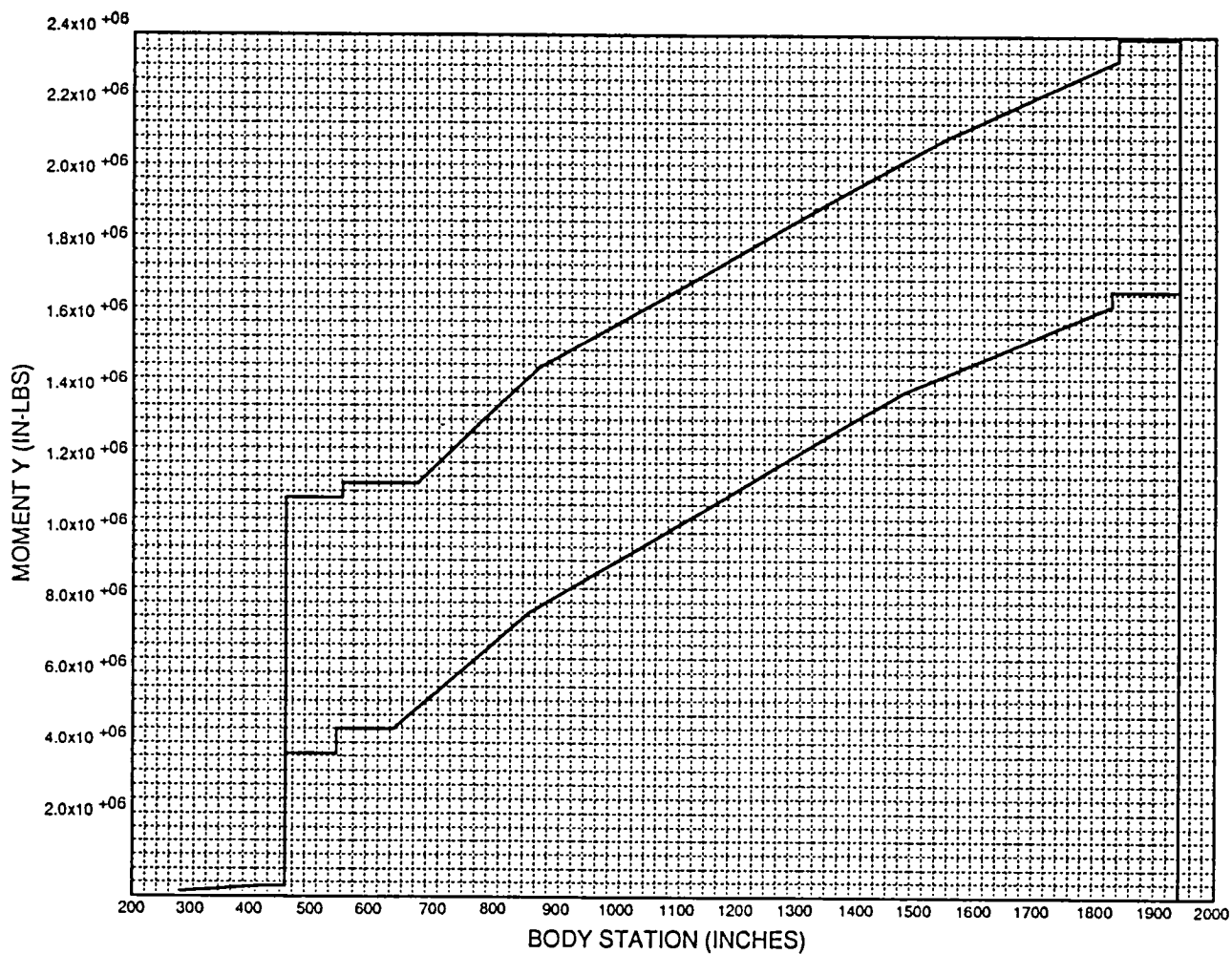
Output of loads as described in this section become the input for the element dynamics and structural assessment analysis (internal loads) to be discussed in the next section.

The importance of the overall loads analysis cannot be overstated. As can be seen, the final structural margins are a direct result of the characteristics and accuracy of these loads. Early in a program, procedures, approaches, tools, etc., must be established and controlled to insure this characterization.

IV. ELEMENT STRUCTURAL ANALYSIS

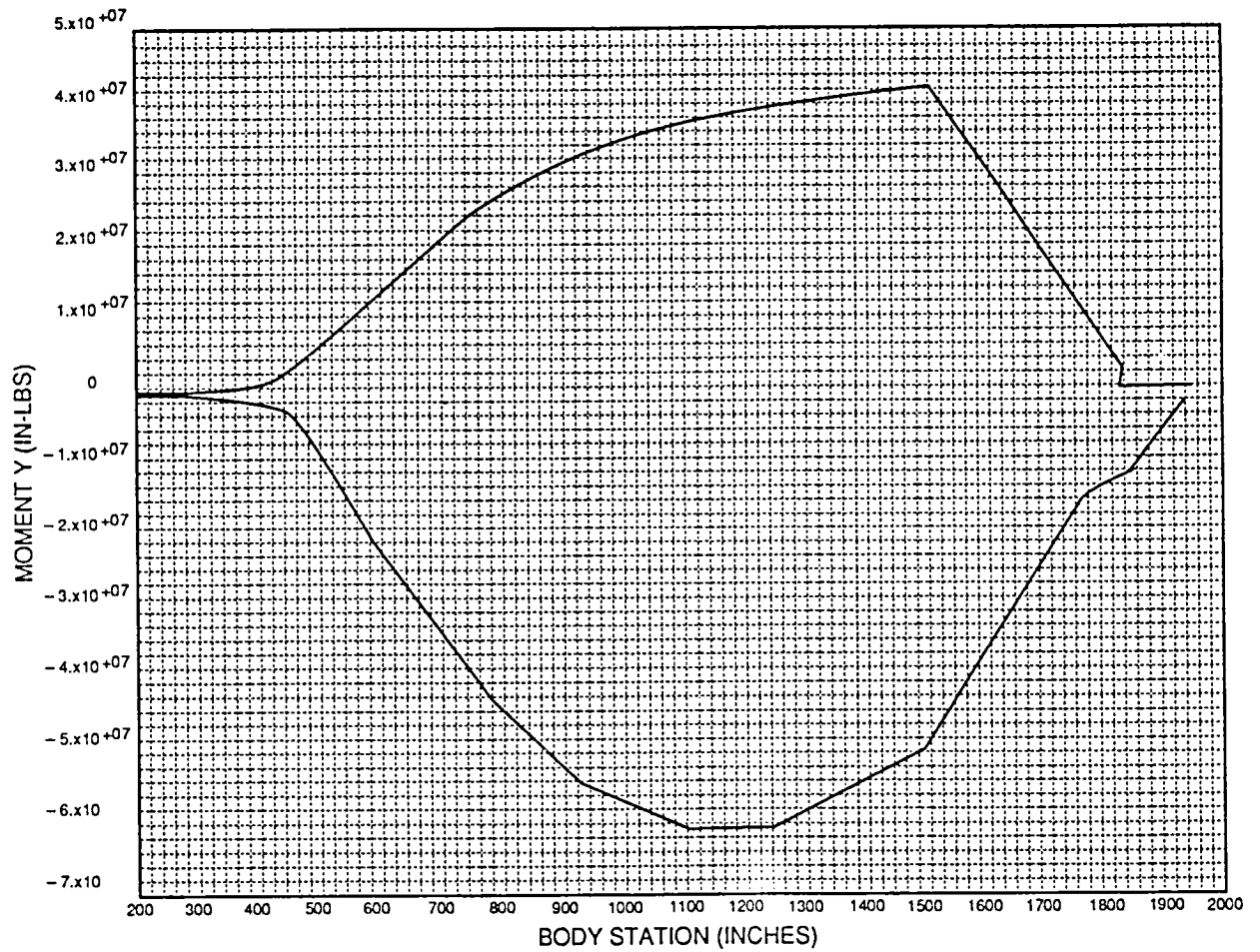
The next phase for determining structural margins is accomplished by the element contractors using the time consistent and running loads generated by the system as discussed in the previous section.

The first step in this phase is the generation of compatible but more detailed dynamic and stress models than the ones derived for the system analysis. The degree and areas for more detail are determined by knowledge of critical areas, such as discontinuities, concentrations, potential nonlinear areas, etc. The same use can be



STATION	MAX CONDITION / MIN CONDITION		STATION	MAX CONDITION / MIN CONDITION	
275.0	SDKSI	SDKSI	395.0	BKSI	SDKSI
447.6	BKSI	BKSI	447.7	SDKSI	BKSI
492.4	BKSI	BKSI	492.5	SDKSI	BKSI
592.0	BKSI	BKSI	771.5	BKSI	SDKSI
931.5	BKSI	BKSI	1107.5	BKSI	SDKSI
1251.0	BKSI	BKSI	1294.5	BKSI	SDKSI
1448.2	SDKSI	SDKSI	1510.9	SDKSI	SDKSI
1511.0	SDKSI	SDKSI	1758.0	SDKSI	SDKSI
1834.8	BKSI	BKSI	1834.8	BKSI	SDKSI
1935.9	BKSI	BKSI	1935.9	SDKSI	BKSI

Figure 24. Shear distribution.



STATION	MAX CONDITION / MIN CONDITION		STATION	MAX CONDITION / MIN CONDITION	
275.0	LMKSA063	LMKSA024	395.0	LMKSA063	LMKSA016
447.6	LMKSA063	LMKSA016	447.7	LMKSA063	LMKSA016
492.4	LMKSA060	LMKSA061	492.5	LMKSA060	LMKSA061
592.0	LMKSA030	LMKSA061	771.5	LMKSA030	LMKSA061
931.5	LMKSA030	LMKSA061	1107.5	LMKSA030	LMKSA061
1251.0	LMKSA030	LMKSA061	1294.5	LMKSA030	LMKSA061
1448.2	LMKSA030	LMKSA061	1510.9	LMKSA030	LMKSA061
1511.0	LMKSA030	LMKSA061	1758.0	LMKSA030	LMKSA051
1834.8	LMKSA030	LMKSA051	1834.8	LMKSA066	LMKSA060
1935.9	LMKSA030	LMKSA051	1935.9	LMKSA102	LMKSA051

Figure 25. Moment distribution.

IVBC-3 LIFTOFF LOADS AT CRITICAL INTERFACES ARE LESS THAN IVBC-2

	IVBC-2 (KLB)	IVBC-3 (KLB)
FT01 (-)	-144	-91
FTB1 (+)	207	193
FTB1 (-)	-206	-106
FTB3 (+)	182	164
FTB3 (-)	-95	-29
P11 (+)	265	187
P11 (-)	-299	-162
P12 (+)	393	187
P12 (-)	-291	-31

NOTE: LOCAL DYNAMIC LOADS ON ORBITAL EQUIPMENT
HAVE INCREASED & ARE UNDER REVIEW

Figure 26. Liftoff loads comparison IVBC-2 and IVBC-3.

ITEM	IVBC-2 (OVERALL LOAD)	IVBC-3 (HI Q LOAD)
FTB 1	207 / -206	49 / - 69
2	207 / -206	59 / -78
3	182 / -95	88 / 9
4	95 / -182	- 8 / -89
5	175 /-1654	-955 /-1364
6	175 /-1643	-958 /-1358
9	218 / -305	197 / -222
10	306 / -218	214 / -252 *
P 8	265 / -299	166 /-170
9	393 / -291	241 /-117
10	202 / -212	*203 /-287 *
11	265 / -299	184 /-133
12	393 / -291	195 / -94
13	207 / -193	180 /-250 *

Figure 27. Max Q loads comparison IVBC-2 and IVBC-3.

made here of stress and loads transformations. Several choices have to be made in determining the details of these models. These include but are not limited to the following:

- Element mesh and sizes
- Element type
- Symmetrical or not
- Nodes
- Degrees of freedom
- Local geometries
- Welds
- Connectors.

Based on these and other considerations, the models are developed and verified using standard check criteria and available test data or by special test.

The next step uses the system analysis outputs, forces, and moment interface time histories, or the running loads, as forcing functions and applies them to this model to determine basic detailed element response. Describing equations, etc., are derived as discussed under systems loads and solved in a comparable manner. Figure 28 illustrates the SRB model and the two types of system force outputs being applied (not concurrently). Output of these analyses are either dynamic responses or stresses. This level of analysis will accomplish several important tasks as well as providing the forcing functions or interface forces for a more detailed substructure analysis. These tasks are:

- 1) Definition of critical areas.
- 2) Structural margins for the general structural areas.
- 3) Forcing functions for substructure analysis.
- 4) Correlation with test.
- 5) Identification of flight event design cases.

Figure 29 shows the identification of design events for the SRB. The general margins of safety determined in this manner for the solid rocket motor are shown on Figure 30. Ultimate margins of safety are determined by multiplying the ultimate safety factor and the limit stress, dividing this product into the material ultimate strength, and from the resulting quotient, subtracting one. Yield margins are defined similarly. Negative margins of safety are unacceptable. All margins of safety must be non-negative. Therefore, the formula is:

$$M.S. = \frac{F_{TU}}{1.4 \times F_t} - 1 \quad , \quad M.S. > 0 \quad .$$

One final case is shown to illustrate the results of this element level analysis. During the SSME buildup case at liftoff, the thrust forces introduce a design bending moment into the SRB. This moment is taken out through the four holddown bolts at the base of each SRB aft skirt. Figure 31 shows the resulting stress in the SRB at three vehicle locations. The stress for each station is plotted circumferentially. Notice how

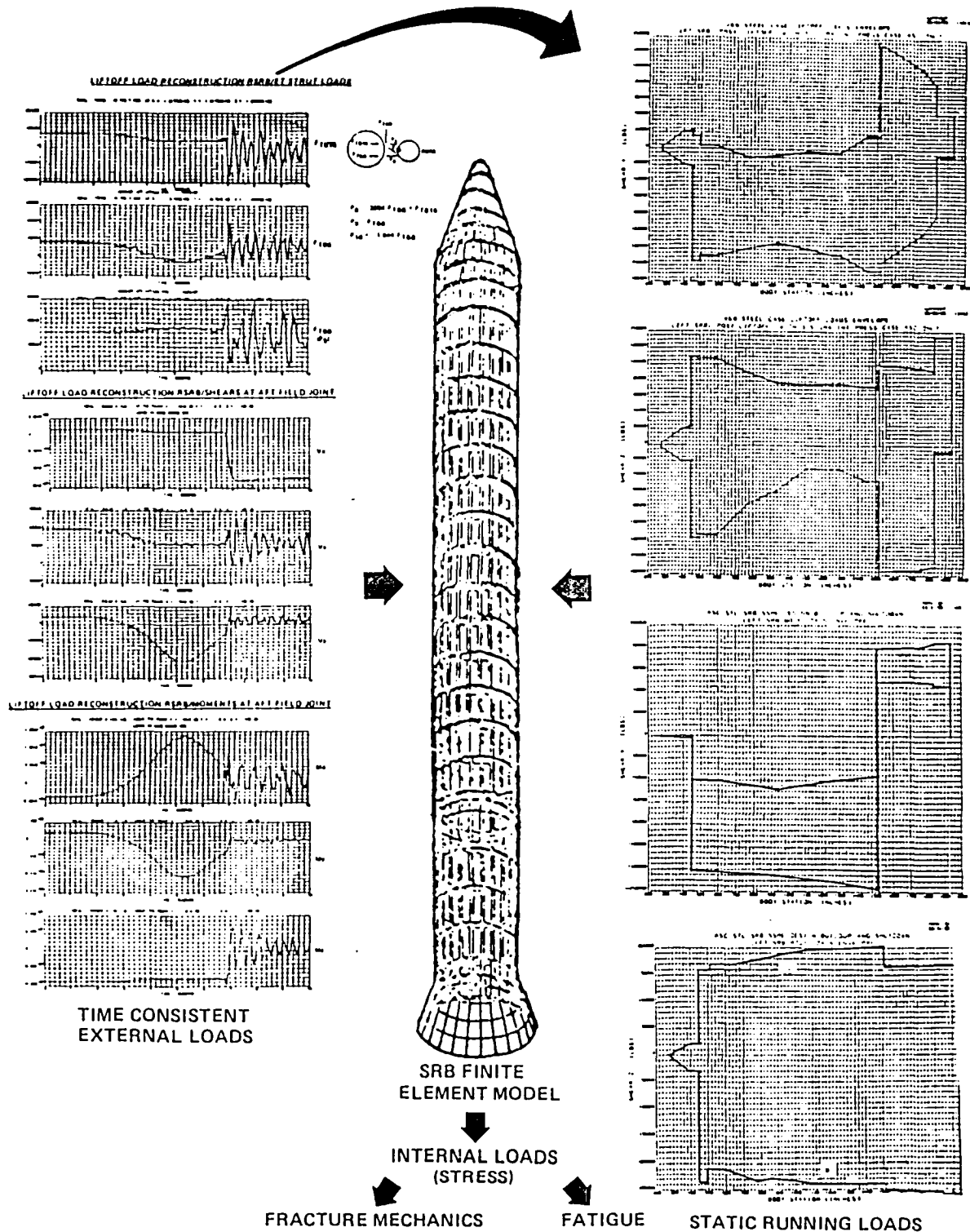


Figure 28. SRB transient and max-min loads.

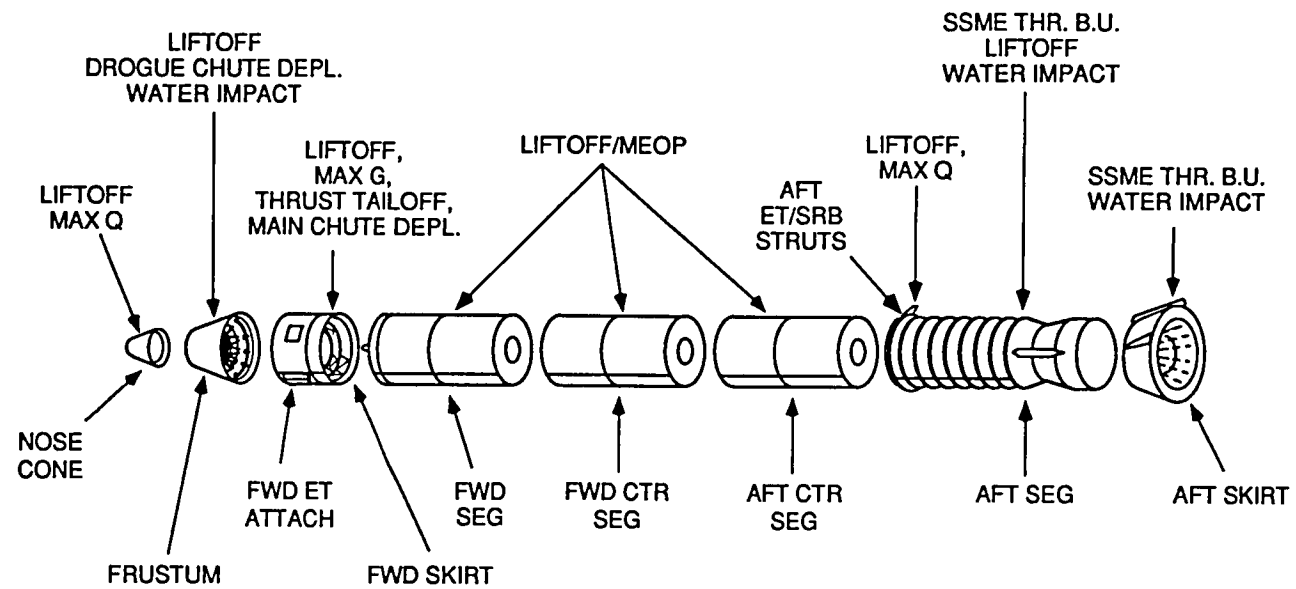


Figure 29. SRB design load events.

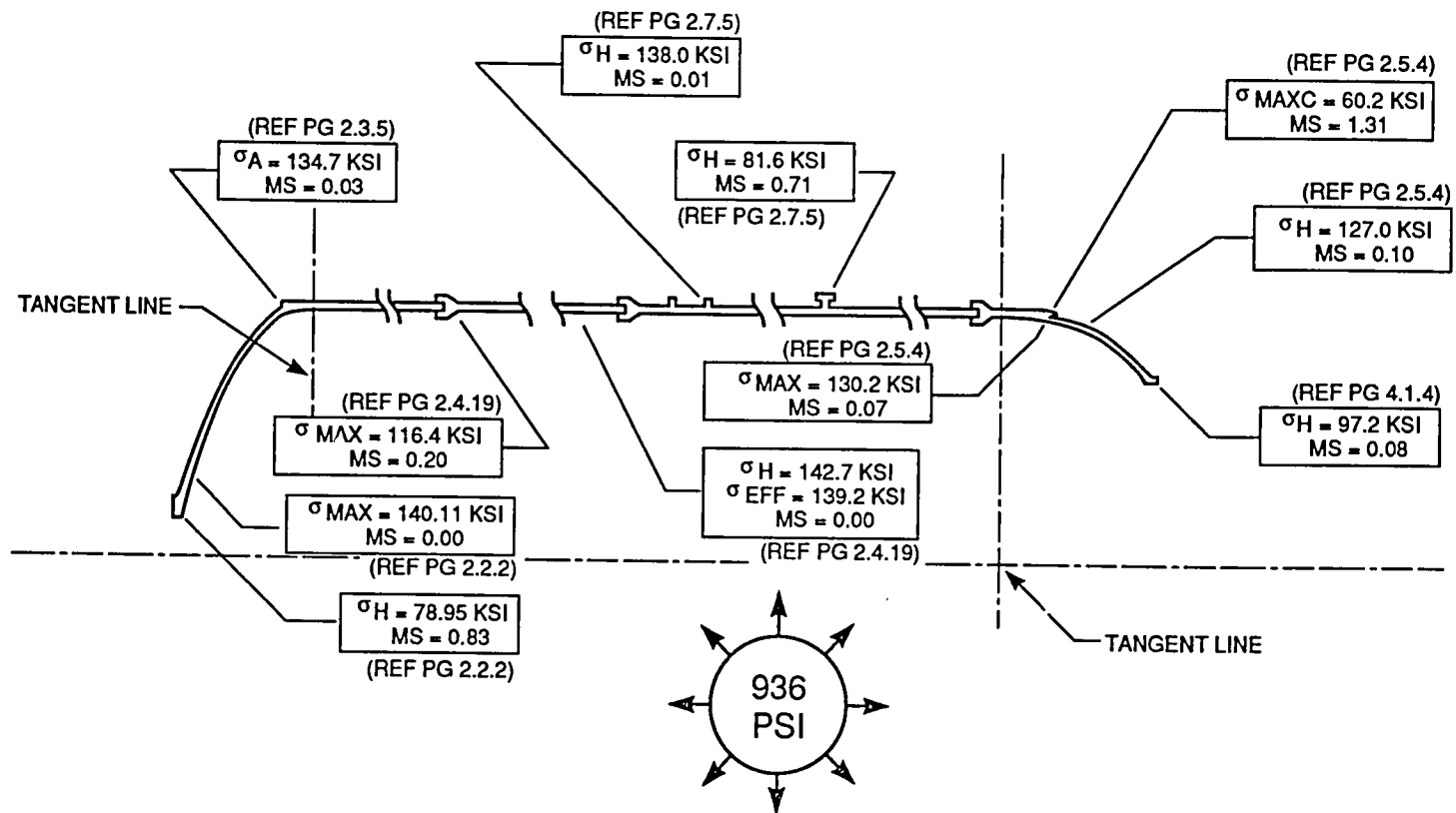


Figure 30. SRM case stress summary.

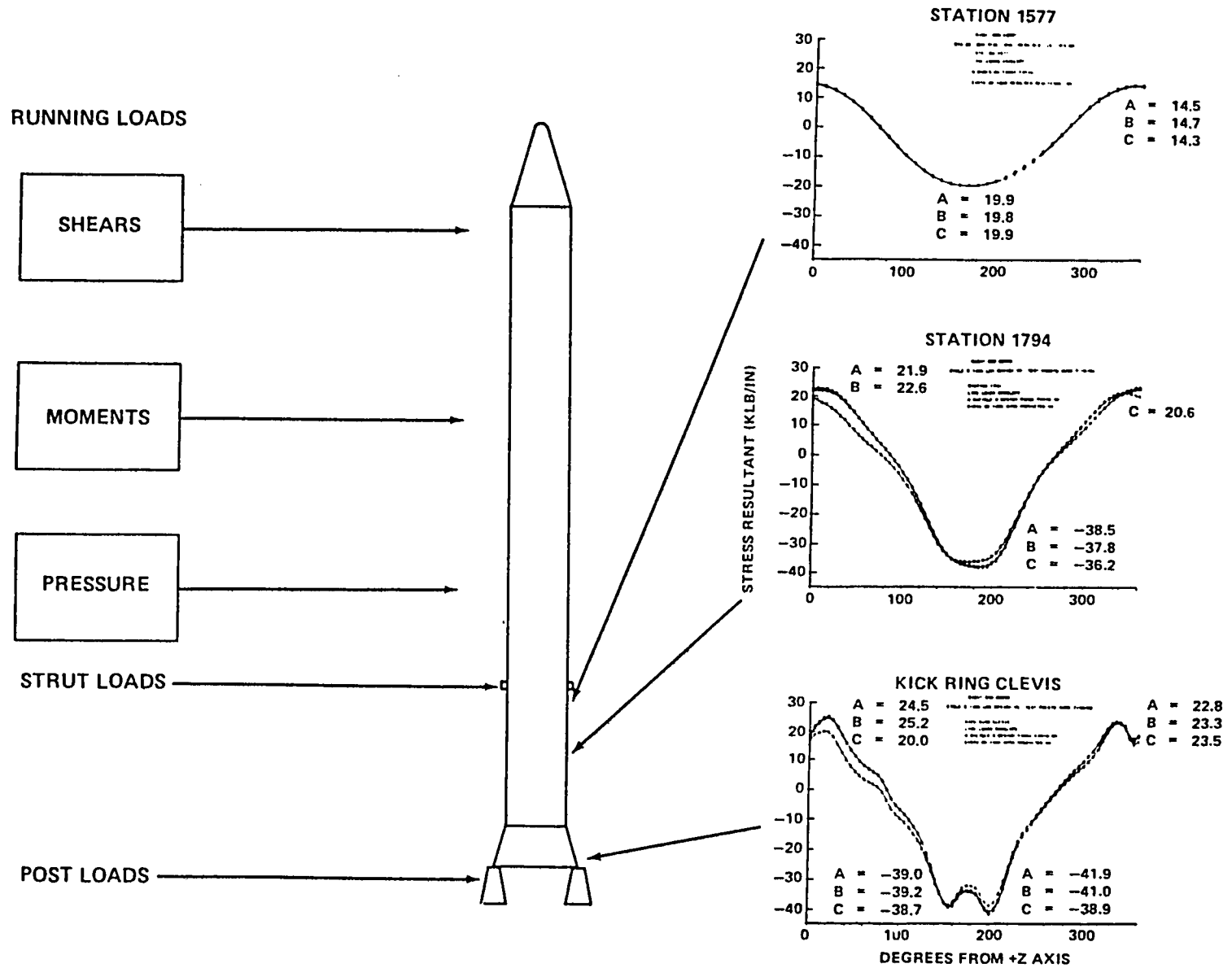


Figure 31. SRB/SRM stress distribution.

the stresses peak near the holddown bolts. This peak load reduces rapidly with distance up the SRB, disappearing near the SRB ET attach ring. In each of these cases, the stress peaks are known as stress discontinuities, and origin and cause are readily recognized by the analyst because of the abrupt change in structural geometry, boundary load, or metallurgical properties. A difficult weld is an example of the latter. ET and SSME examples are not given but can be found in References 2 and 3.

V. SUBELEMENT AND LOCAL ANALYSIS

This phase of the analysis is very critical. It is at this level where all fracture mechanics, NDE, nonlinear stress analysis, fastener analysis, stability, and critical margins are determined. This more indepth evaluation requires more detailed models of critical subelement and possible nonlinear analysis techniques. Here the modeling assumptions, code choices, analysis levels, linear versus nonlinear, etc., can produce completely erroneous or very accurate predictions, depending on the engineer's judgments. Again, it starts with the choice of model mesh, elements, and codes as discussed previously. This choice is made based on the hand analyses, etc., discussed up front. Also, the use of load indicators, stress and loads transformations can be used as a time saver for many of these analyses. Since the analysis is dealing with more localized areas, it is critical that the engineer understands finite element modeling in all respects and not use programs, codes, etc., in a black box manner. Several books and papers exist on this subject. Reference 4 is a typical example. A brief overview of finite elements follows to provide a basis for the other discussions.

The finite element approach is based on the idea that you can take a very complex problem and break it up into many subsets (finite elements) of single problems with simple assumptions yielding approximate solutions, which with proper care in element choices will converge close to the real solution (Fig. 32). The general concept is illustrated in Figure 33, showing how the area of a circle can be approximated using either a circumscribed or inscribed polygon. As the number of elements of the polygon increase so does the solution convergence. Applying the concept to a structure and solid mechanics problem, the approach is shown in Figure 34 and illustrated in Figure 35. In this case, there are three areas of consideration used in the idealization.

1) Design Conditions

- o Geometry
- o Loading
- o Material Properties
- o Boundary Conditions

2) Element Types

- o Simple Frame
- o Plane Stress
- o Solid Elements
- o Axisymmetric Solid
- o Flat Plate Bending
- o Axisymmetric Thin Shell
- o Curved Thin Shell

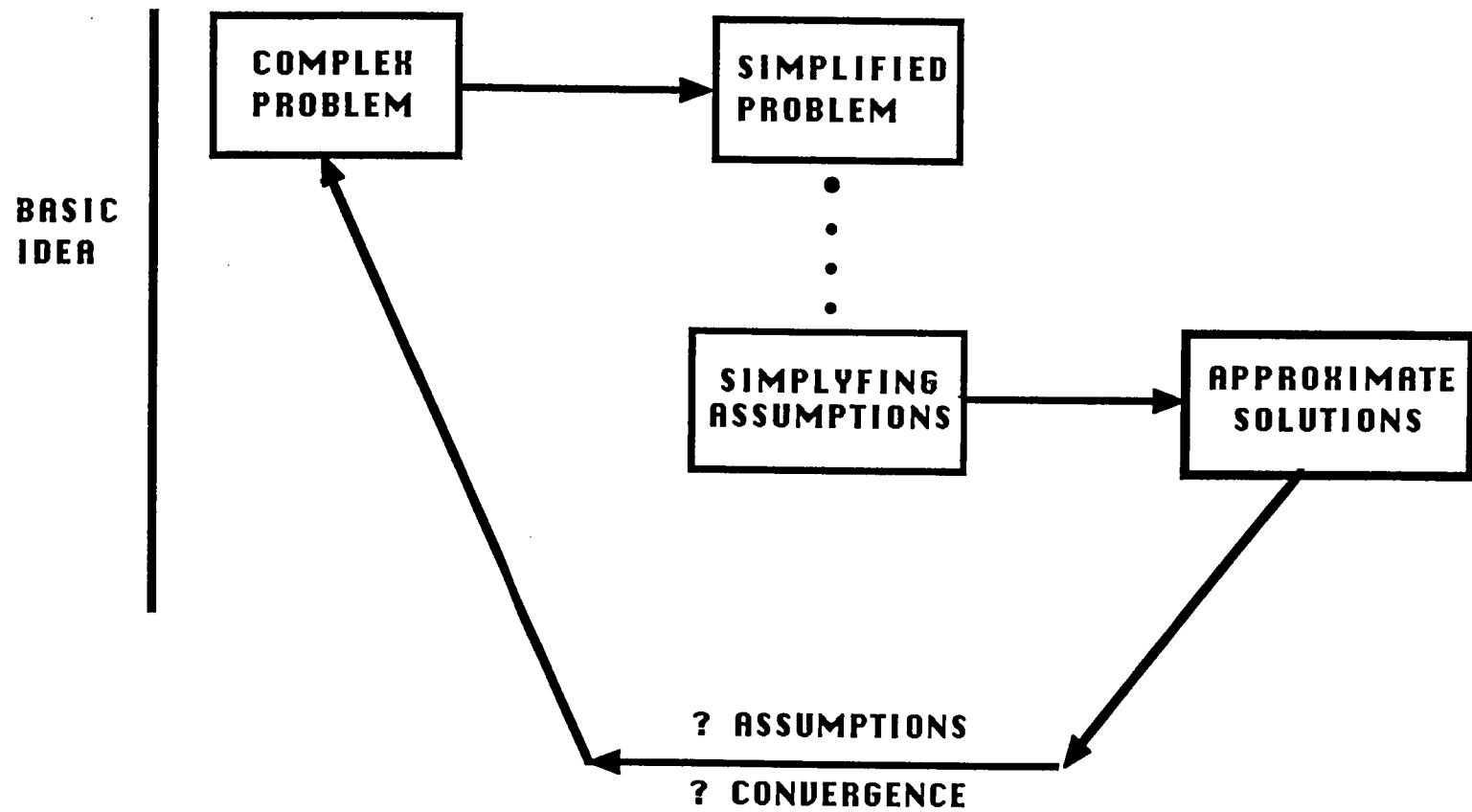


Figure 32. The finite element method.

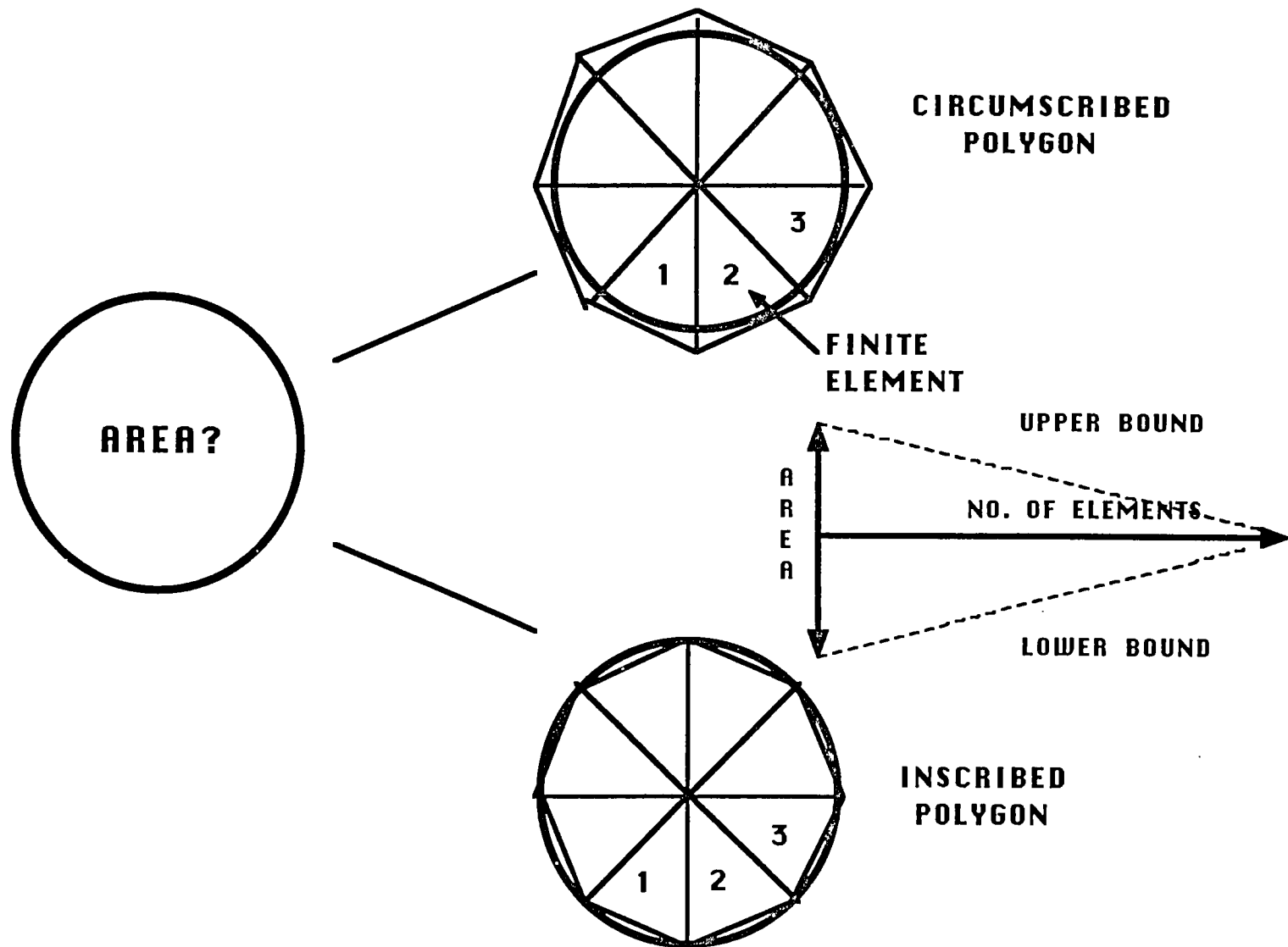


Figure 33. The finite element general concept.

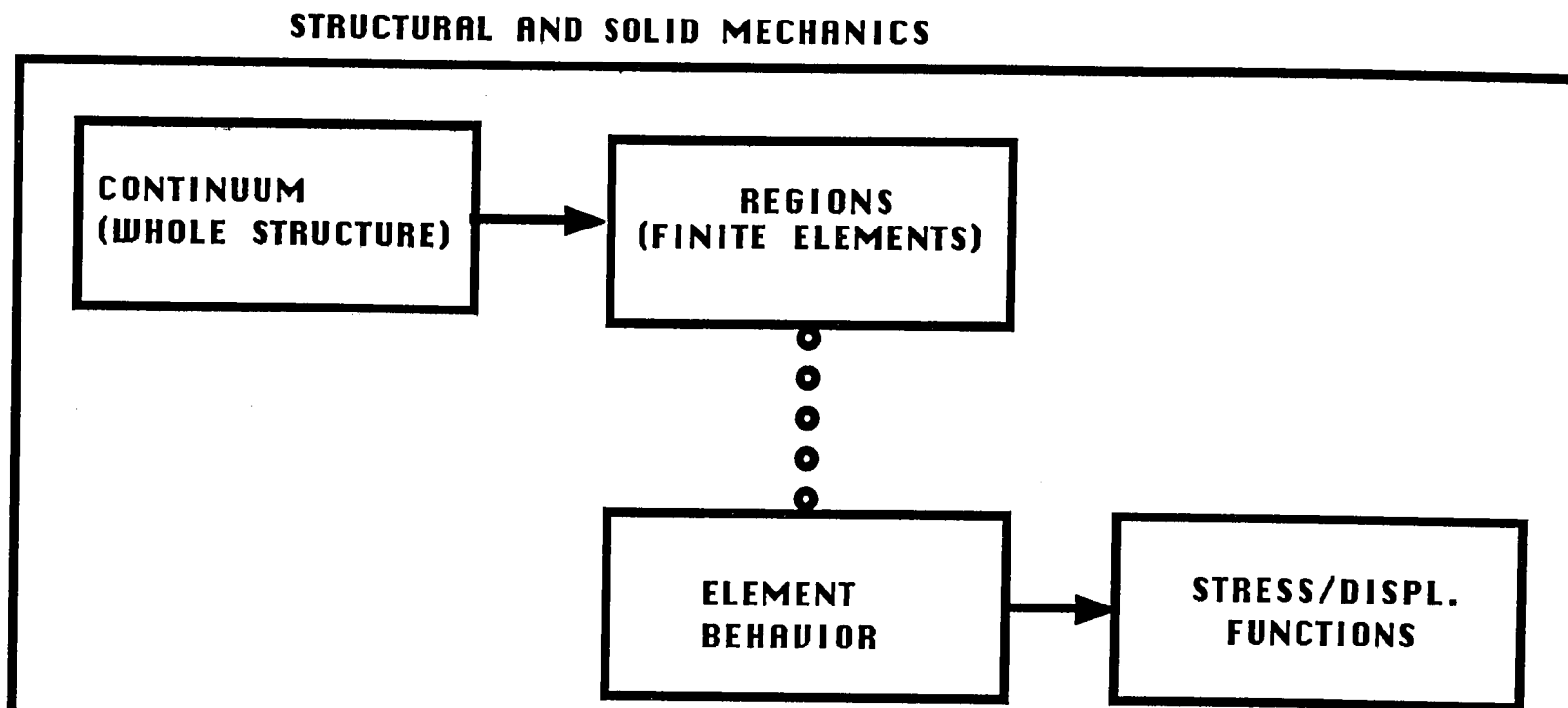


Figure 34. The finite element basic concept.

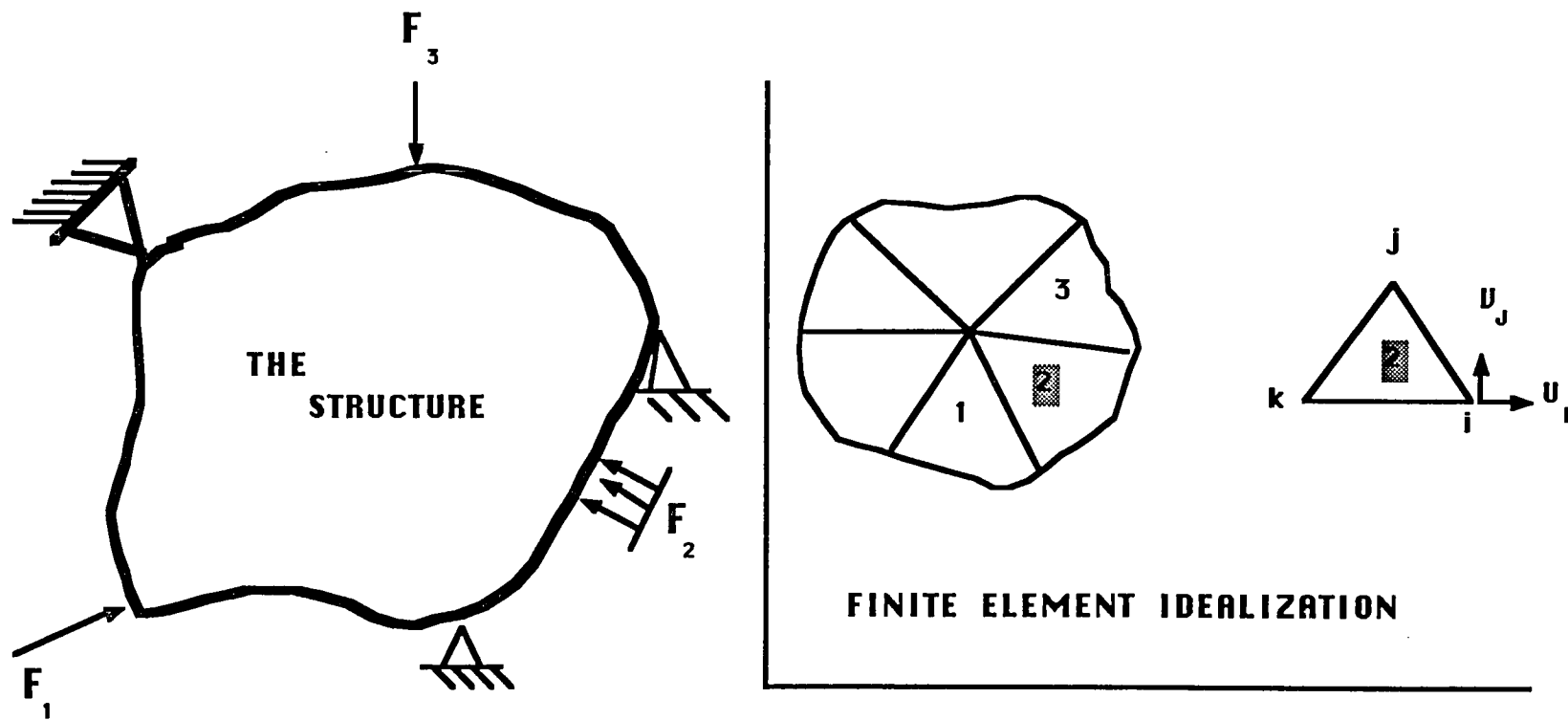


Figure 35. The finite element general approach.

3) Governing Equations

- o Equilibrium Conditions
- o Compatibility Conditions (relate stress to strain)
- o Kinematic Conditions (relate strain to displacements).

The model is developed by writing an assumed displacement-based function which gives the element displacement as a function of a shape function and node displacements. Then relationships between displacement and strain, strain and stress, and stress and joint forces are written, then combined to give the overall element equation. As the element complexity grows, so do these functions. The general set contains:

- o Shape Functions
- o Displacement - Strain
- o Strain - Stress
- o Stress - Joint Forces
- o Stiffness Equation.

The choice of elements then is determined by the need to properly represent shapes, stress, etc. Key factors are the characteristics of the areas being modeled and whether elastic or plastic (nonlinear) analysis is required. For very complex analysis, many node solid elements are required. It should be warned, however, in the concern to get details be sure that basic length, width, depth ratios do not violate sound principles; e.g., long, thin, deep elements usually give problems. For very large and complex structures (such as a Shuttle element), demand or available finite element solving equipment is exceeded, and the total structure is subdivided according to specific considerations. These subdivisions or components are called substructures or subelements.

Using these basic principles and concepts to varying degrees throughout a subelement, the subelement model is constructed and validated as before. The interface forces evolved from the system analysis through the element analysis are now used as forcing functions or force distributions on the model. Figure 36 shows this approach being used to predict the aft SRM field joint response during liftoff. This is a combined static and dynamic analysis using a detailed finite element model with greater detail in the joint region. The SRB E-ring model and struts are included. Figure 37 shows these results for the Shuttle flight through maximum dynamic pressure. Notice the detail of the input forcing functions required and the output details. Cautions must be raised in that the subelement model size must be large enough to distribute out the loads and balance the set. Material properties, etc., must match these same details or errors result.

References 2 and 3 contain many examples of this type analysis for various space projects and other Shuttle elements.

The final analysis step uses the same approach as this subelement step using the results from the subelement analysis as forcing functions for a critical area within the subelement. Greater care is required for the very detailed model of this critical area, since both elastic and plastic (nonlinear) analytical techniques must be used. Element choices must be done with great care. The SRB aft skirt and the corresponding post to skin weld area are critical areas (Fig. 38). Solid elements with good shape functions and additional nodes are required. Material characteristics and variations in critical regions are accomplished. Using this model (critical areas), the

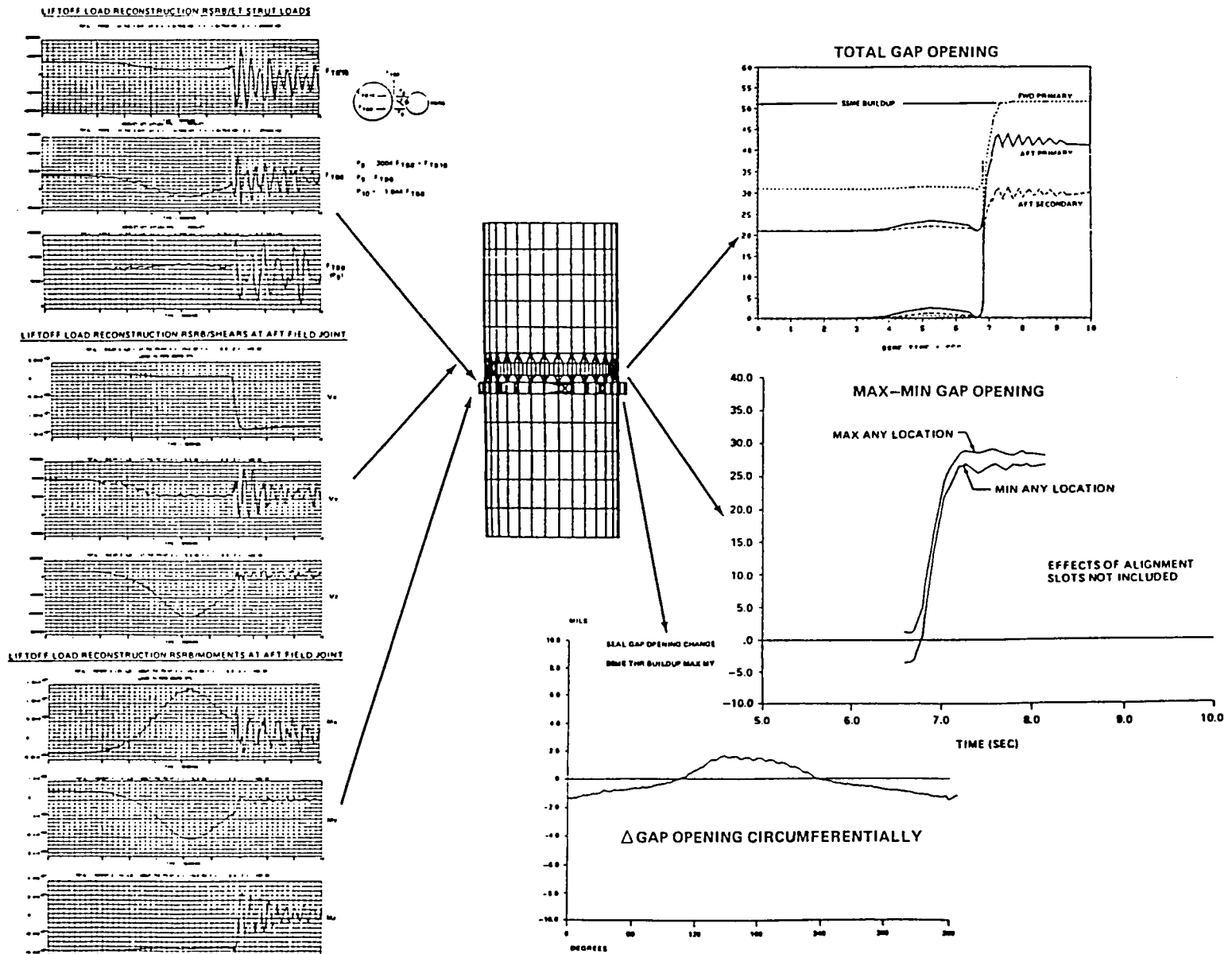


Figure 36. SRM field joint response, liftoff.

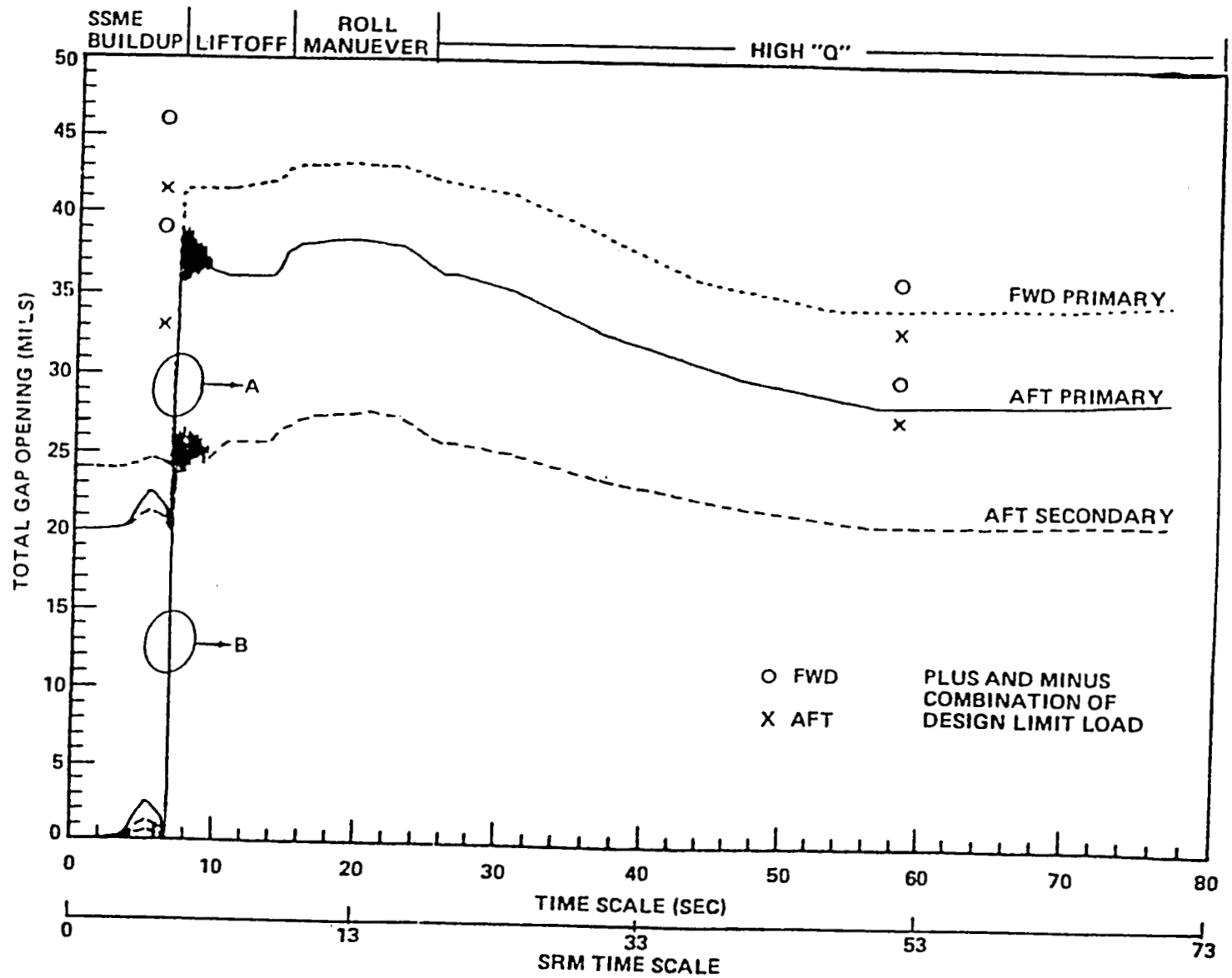


Figure 37. SRM field joint response, Max Q.

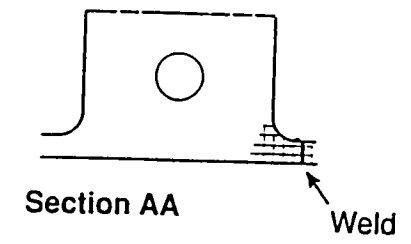
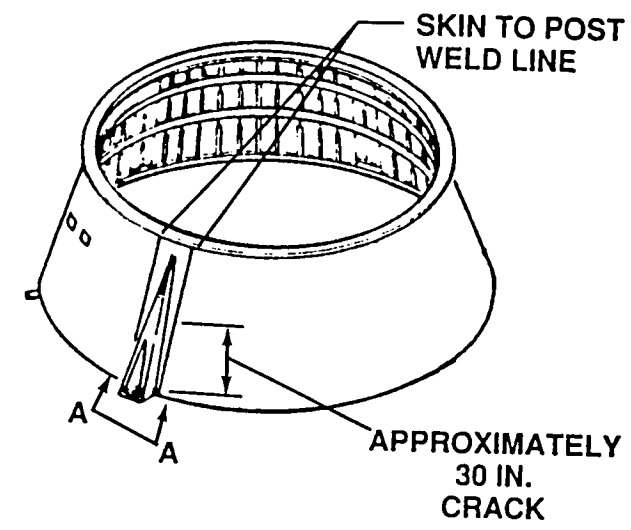
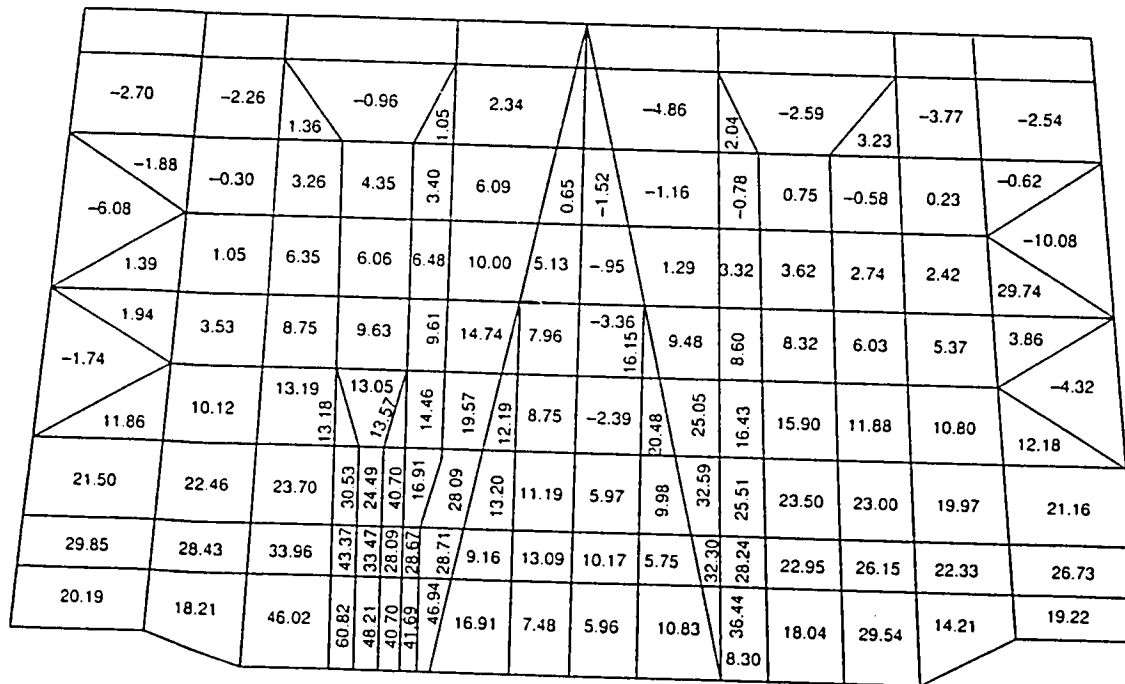


Figure 38. SRB aft skirt stress distribution.

dynamic and stress analysis directly provides the margins of safety; however, this is not the end. At least five other analyses are required using detailed data from this critical analysis as inputs.

1) Fracture mechanics analysis including lifetime, critical flaw size, and NDE requirements.

2) Fatigue (lifetime specifications).

3) Stability.

4) Nonlinear plastic analysis.

5) Nonlinear jointed structural analysis.

These analyses [1,5-12] require judicious choice of analysis codes, materials data, and test derived parametric data. Bolted joints are a problem, since individual bolt loading and local yielding are not deterministic. Elastic analysis could easily show major problems when no problem exists. In other words, bad assumptions produce totally erroneous analysis. The starting point for fracture analysis is accurate stress at the potential failure locations. Many examples and additional guidelines could be given, but are beyond the scope of this paper. The same is true for fatigue. These analysis approaches are not discussed in this report, but are covered in detail in NASA SP design documents. These are left to the reader [1,4-12].

VI. SUMMARY

Determination of space vehicle structural margins and capability is a very complex problem, requiring many steps, great skills, computer capability, software, test, and flight verification. The basic steps in outline form can be summarized for space systems as:

1. Develop compatible element models
2. Verify models
 - a. Analytical
 - b. Test
3. Assemble models into overall systems model
4. Verify system model
 - a. Analytical
 - b. Test
5. Determine natural and induced environments with expected variations
6. Verify environments
 - a. Analytical
 - b. Experimental
 - c. Flight

7. Calculate system loads for all critical element areas and all flight events
8. Verify loads
 - a. Analytical
 - b. Flight
9. Develop more detailed element models
10. Verify models
 - a. Analytical
 - b. Test
11. Determine element local response and margins using system loads outputs as forcing functions
12. Verify loads
 - a. Analytical
 - b. Test
13. Develop subelement models
14. Verify subelement models
15. Determine subelement responses and margins
16. Develop local critical areas very detailed models
17. Determine critical areas responses and margins using subelement responses as forcing functions
18. Verify margins
 - a. Analytical (various codes)
 - b. Test
19. Perform additional analysis using critical area or subelement responses as required
 - a. Fracture mechanics
 - b. Fatigue
 - c. Stability
 - d. Nonlinear plastic analysis
 - e. Nonlinear bolted, etc., joints.

Some steps may be eliminated; however, indepth assessment should be made before any are deleted. Verification of all models and analyses is imperative. Pre-verification test analysis must be performed to guide the test, provide proper instrumentation, and data evaluation. Post test analysis including model/analysis update must be accomplished so that adequate tools are in hand for design changes, deviation assessment, and operational constraint determination. Using these approaches, a safe, reliable space mission can be accomplished. Deviation in any area can lead to programmatic adversities at best.

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APPROVAL

STRUCTURAL MARGINS ASSESSMENT APPROACH

By Robert R. Ryan

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.



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